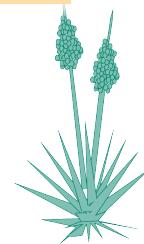




UNM

# Recent Results on Heavy Baryons from CDF

Igor V. Gorelov  
*University of New Mexico*  
*On behalf of the CDF Collaboration*



Joint Experimental-Theoretical Physics Seminar  
13 December 2013

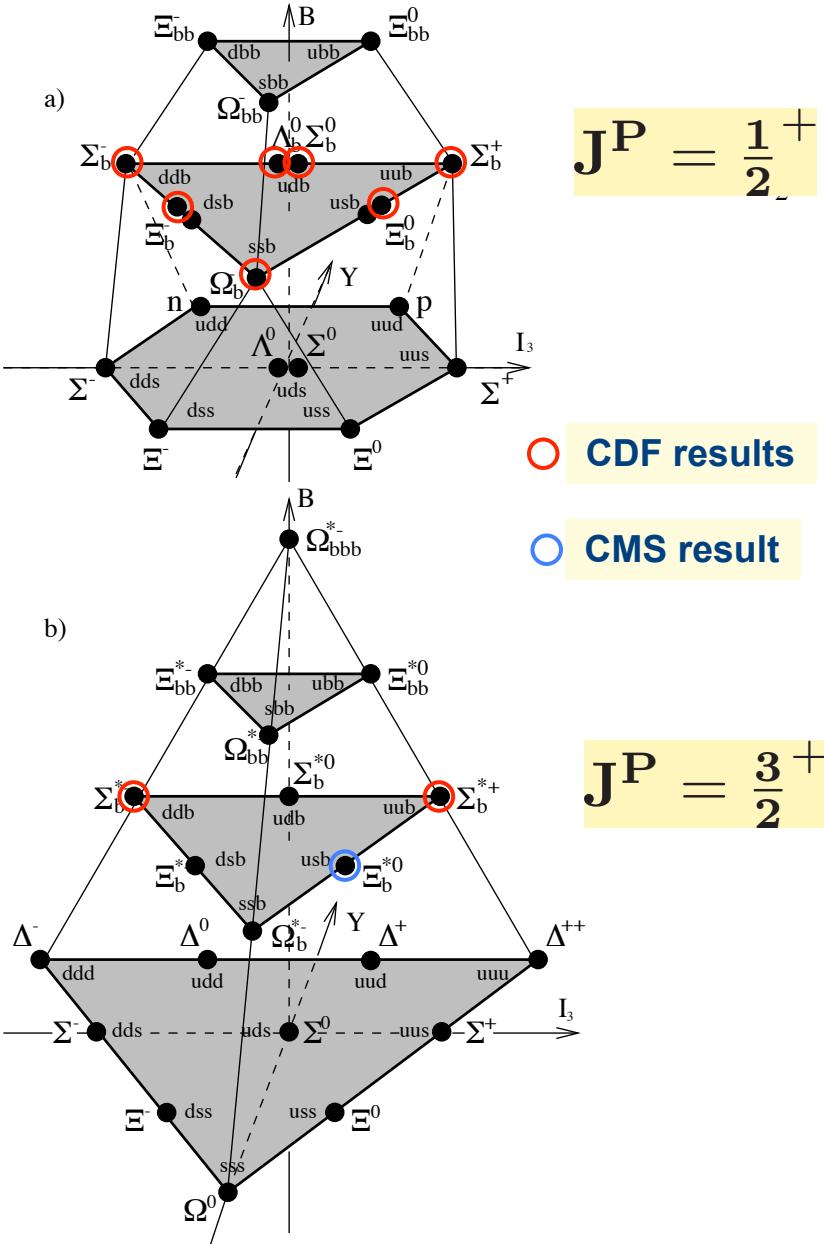
# Outline

- **Introduction**
- **CDF Detector and Triggers**
- **Bottom Baryon Ground States: Properties**
- **Bottom Baryon Resonant States**
- **Conclusions**

# b-Baryons

## ⇒ Baryons: Bottom Sector

- **Baryon:**  $q_{f_1}, q_{f_2}, q_{f_3}$
- **Ordinary  $SU_f(3)$  with**  
 $f_i \in u, d, s$
- **Bottom  $SU_f(5)$  with**  
 $f_i \in u, d, s, c, b$
- $Y \equiv \mathcal{B} + S + \frac{B}{3}$ , hypercharge.
- **Bottomness:**  $B = -1$ , for  $b$ -quark.
- **$SU_f(5)$  heavily broken due to masses of heavy quarks.**

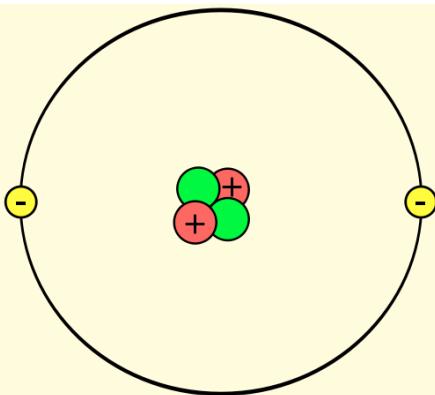


# Motivations (I)

- **Atomic physics:**

atom He ( $A = 4$ ,  $Z = 2$ )

- **Nucleus:**  $2p^+ + 2n$   
of  $M \approx 4 \text{ GeV}/c^2$
- **Orbiting electron pair:**  
 $e^-e^-$



- **QCD physics:**

**bottom baryon**, ( $b q_1 q_2$ ), as  
“He” of QCD

- **$b$ -quark as a “nucleus”,**  
 $m_b \approx 5 \text{ GeV}/c^2$
- **light di-quark  $q_1 q_2$  as an**  
“electron pair”
- **color charge field in**  
**bottom baryon replaces**  
**electric charge field in real**  
He

# Motivations (II)

- The bottom quark baryons as a useful QCD laboratory
  - to study non-perturbative QCD in a different regime w.r.t. the light baryons
  - observing new baryon states, measuring their properties sets experimental constraints to the QCD models
- Well established  $c$ - baryon sector
- the high  $b$ -quark production rates and energy at Tevatron provided access to data samples enriched with the heavy bottom baryon states.
- yet, currently only small number of statistically limited  $b$ -baryon observations

# Phenomenology (I)

## ⇒ Heavy Quark Symmetry (HQS)

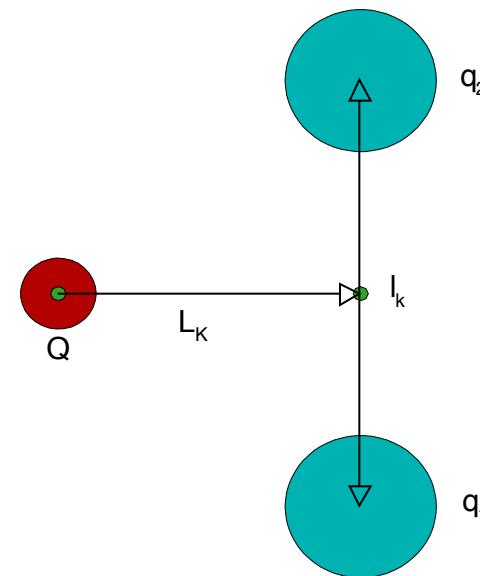
- QCD of a heavy baryon,  $(Q q_1 q_2)$ , is simplified in a presence of a heavy  $Q$
- $m_Q \gg \Lambda_{\text{QCD}} \gg m_{q\bar{q}}$ ,  $m_Q \simeq 4.8 \text{ GeV}$ ,  $Q \equiv b$
- in  $m_Q \rightarrow \infty$  limit:  $Q$  is a static color source of a gluon field in the baryon rest frame (Isgur & Wise, 1989-90)
  - approx. SU(2) symmetry: the light  $q_1 q_2$  properties of the  $c$ -hadron,  $\Lambda_c^+$ , related to  $b$ -hadron,  $\Lambda_b^0$  with  $c \leftrightarrow b$  exchange.
  - the spin of the heavy quark,  $S_Q$  decouples from the gluon field, from  $q_1 q_2$  degrees of freedom
  - Heavy baryons' properties are governed by the dynamics of the  $q_1 q_2$  in the gluon field

# Phenomenology (II)

- Models exploiting HQS are collectively identified as Heavy Quark Effective Theories
- Heavy baryons can be described by the quantum numbers

- spin and mass of the heavy quark  $S_Q, m_Q$
- spin and mass of the light di-quark  $S_{qq}, m_{qq}$

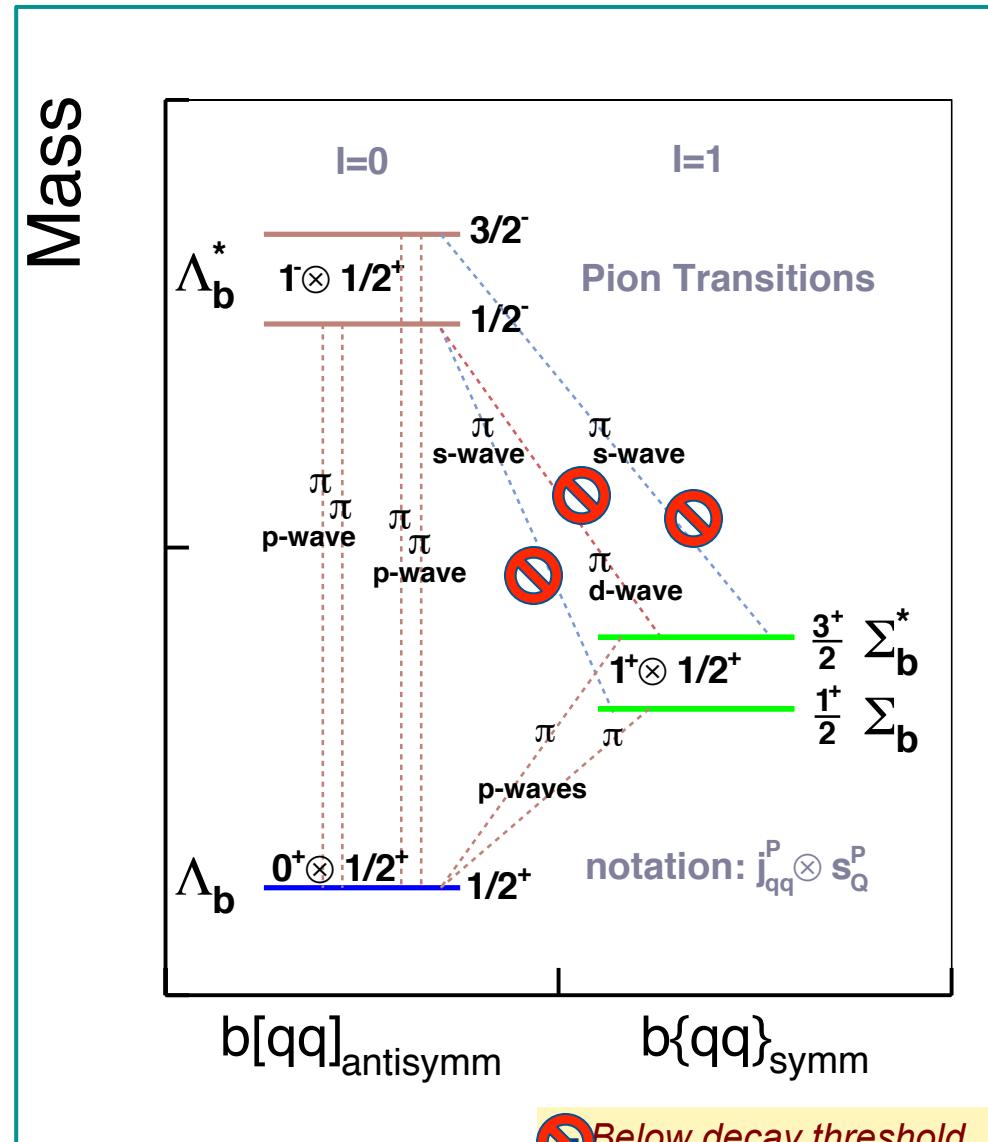
Qq<sub>1</sub>q<sub>2</sub> System: Orbital Angular Momenta.



$$\begin{aligned}\Rightarrow \bar{\mathbf{J}}_{qq} &= \bar{\mathbf{S}}_{qq} + \bar{\mathbf{L}}_{qq} \\ \Rightarrow \bar{\mathbf{J}}_{Qqq} &= \bar{\mathbf{S}}_Q + \bar{\mathbf{J}}_{qq}\end{aligned}$$

# Hadron Decay Modes of Bottom Baryon Resonances

- Resonant, *S*-wave, states:  
 $\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi^\pm$ 
  - single-pion  $\pi^\pm$  in *P*-wave
- Orbital excitations, *P*-wave states:  
 $\Lambda_b^{*0} \rightarrow \Lambda_b^0 \pi^+ \pi^-$  given sufficient phase space.
  - di-pion  $\pi^+ \pi^-$  in *P*-wave

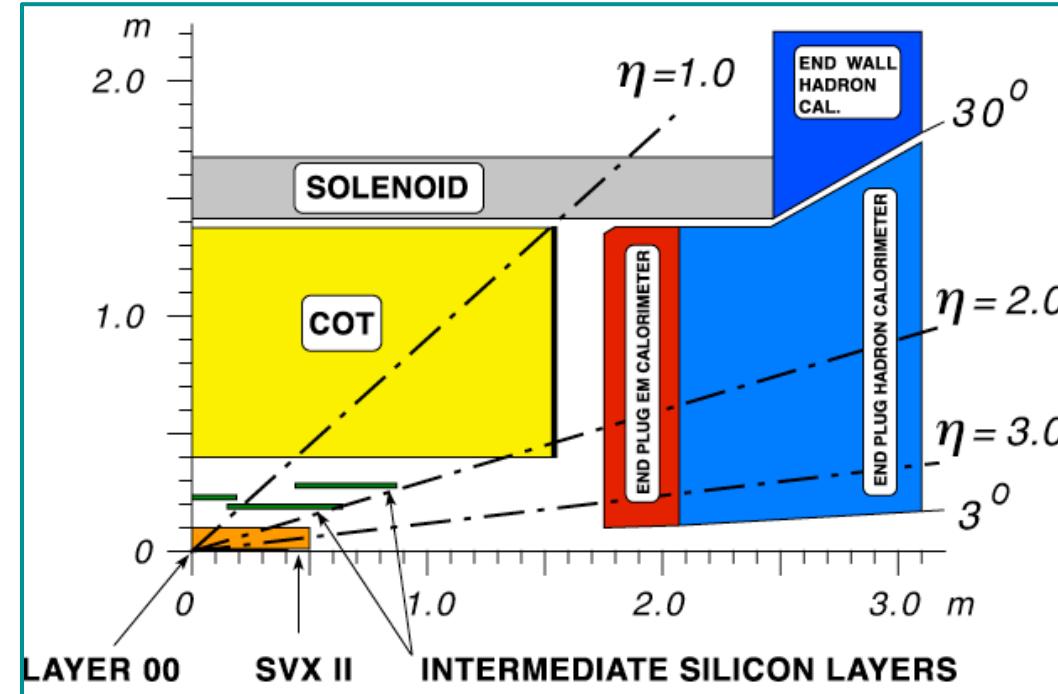


# *b*- Baryons: Experimental Status

State	Composition	J <sup>P</sup>	m, MeV/c <sup>2</sup>	Source
<i>Ground Bottom Baryon States</i>				
$\Lambda_b^0$	$b[ud]$	$(1/2)^+$	$5619.4 \pm 0.6$	PDG
			$5619.44 \pm 0.13 \pm 0.38$	LHCb, 2012+2013
$\Xi_b^- (\rightarrow J/\psi \Xi^-)$	$b[sd]$	$(1/2)^+$	$5790.9 \pm 2.6 \pm 0.8$	CDF, 1st obsrv.
			$5774.8 \pm 11 \pm 15$	D0, 1st obsrv.
			$5795.8 \pm 0.9 \pm 0.4$	LHCb, 2013
$\Xi_b^0 (\rightarrow \Xi_c^+ \pi^-)$	$b[su]$	$(1/2)^+$	$5787.8 \pm 5.0 \pm 1.3$	CDF, 1st obsrv.
$\Xi_b^- (\rightarrow \Xi_c^0 \pi^-)$	$b[sd]$	$(1/2)^+$	$5796.7 \pm 5.1 \pm 1.4$	CDF
$\Omega_b^0 (\rightarrow J/\psi \Omega^-)$	$bss$	$(1/2)^+$	$6054.4 \pm 6.8 \pm 0.9$	CDF
			$6165.0 \pm 10 \pm 13$	D0, 1st obsrv.
			$6046.0 \pm 2.2 \pm 0.5$	LHCb, 2013
<i>S-wave Resonance States</i>				
$\Sigma_b^+$	$buu$	$(1/2)^+$	$5807.8^{+2.0}_{-2.2} \pm 1.7$	CDF, 1st obsrv.
$\Sigma_b^-$	$bdd$	$(1/2)^+$	$5815.2 \pm 1.0 \pm 1.7$	CDF, 1st obsrv.
$\Sigma_b^{*+}$	$buu$	$(3/2)^+$		
$\Sigma_b^{*-}$	$bdd$	$(3/2)^+$		
$m(\Sigma_b^*) - m(\Sigma_b)$			$21.2^{+2.0}_{-1.9} (\text{stat})^{+0.4}_{-0.3} (\text{syst})$	CDF, 1st obsrv.
$\Xi_b^{*0} (\rightarrow \Xi_b^- \pi^+)$	$b\{sd\}$	$(3/2)^+$	$5945.0 \pm 0.7 \pm 0.3$ $\pm 2.7 (PDG)$	CMS, 1st obsrv.
<i>Orbital P- wave Resonance States</i>				
$\Lambda_b^{*0}$	$b[ud]$	$(1/2)^-$	$5911.97 \pm 0.12 \pm 0.02$ $\pm 0.66 (\Lambda_b^0)$	LHCb, 1st obsrv.
$\Lambda_b^{*0}$	$b[ud]$	$(3/2)^-$	$5919.77 \pm 0.08 \pm 0.02$ $\pm 0.66 (\Lambda_b^0)$	LHCb, 1st obsrv.

# CDF II Detector

- Axial magnetic field: 1.4 T
- Inner tracking system
  - Si VerteX detector, 1+5 layers
  - Intermediate Si Layers, ISL
  - VX resolution:  
 $\sigma_{xy} \approx 15 \mu\text{m}$ ,  $\sigma_z \approx 70 \mu\text{m}$
  - I.P.:  $\sigma_{d_0} \approx 40 \mu\text{m}$ , with  
 $\sigma_{beam} \approx 32 \mu\text{m}$  included
- Cylindrical main drift chamber (COT)
- The track  $p_T$  resolution:  
 $\sigma(p_T)/p_T^2 \approx 0.07\%$ ,  $p_T$  in  $\text{GeV}/c$

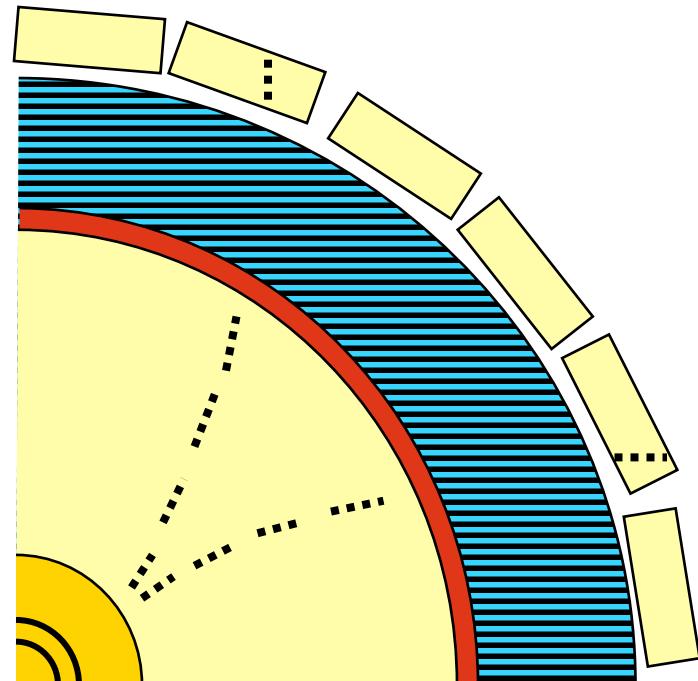


## • Muon Detector System

- $|\eta| < 1.0$ ,  $p_T(\mu) > 1.4 \text{ GeV}/c$
- the measurements are matched with COT tracks.

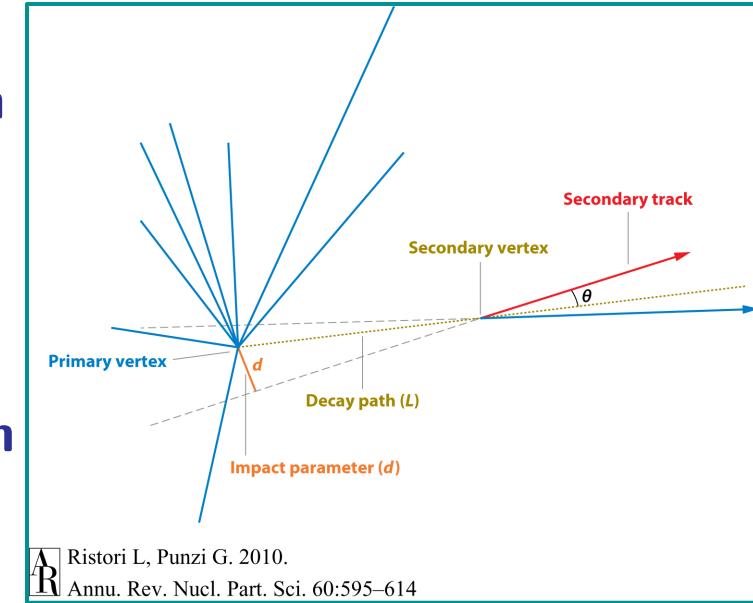
# J/ $\psi$ Triggers

- need  $\simeq 10^{-3}$  rate reduction  $\Rightarrow$
- $J/\psi$  di-muon trigger: reach of  $B^+ \rightarrow J/\psi K^+$ ,  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  etc.
  - tracks reconstructed in COT with  $p_T > 1.5 \text{ GeV}/c$  matched with hits in the muon detectors.
  - opposite charge di-muons in  $J/\psi$  range:  $M(\mu^+ \mu^-) \in (2.7, 4.0) \text{ GeV}/c^2$



# Hadron Triggers

- Exploit long  $ct$  of ground state  $b$ -hadrons.
  - $\geq 2$  tracks in main drift chamber with  $p_T > 2 \text{ GeV}/c$  each,
  - matched with hits in Si detector:
    - ◊ offline-like  $\sigma_{d_0}(\text{total}) \approx 50 \mu\text{m}$  achieved,
    - ◊ tracks with  $d_0 > 100 \mu\text{m}$  each can be selected.
- The trigger biases proper decay time: not used for mean life measurements in presented analyses.



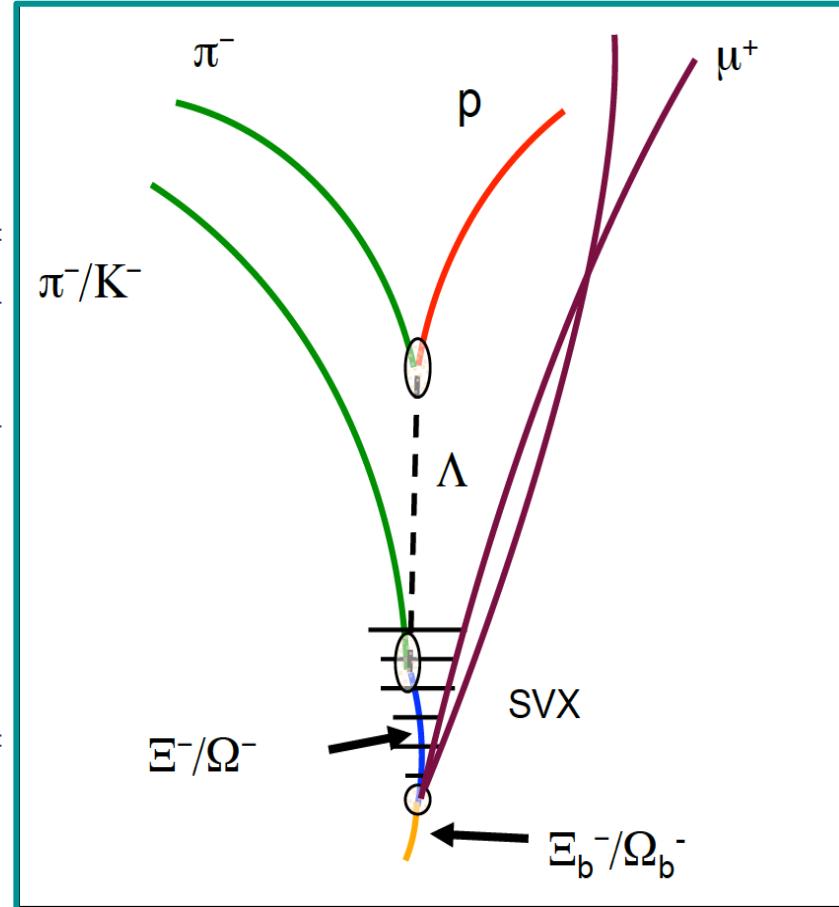
# **Bottom Baryon Ground States: Mass and Mean Life**

# Reconstruction of

## $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ , $\Xi_b^- \rightarrow J/\psi \Xi^-$ , $\Omega_b^- \rightarrow J/\psi \Omega^-$

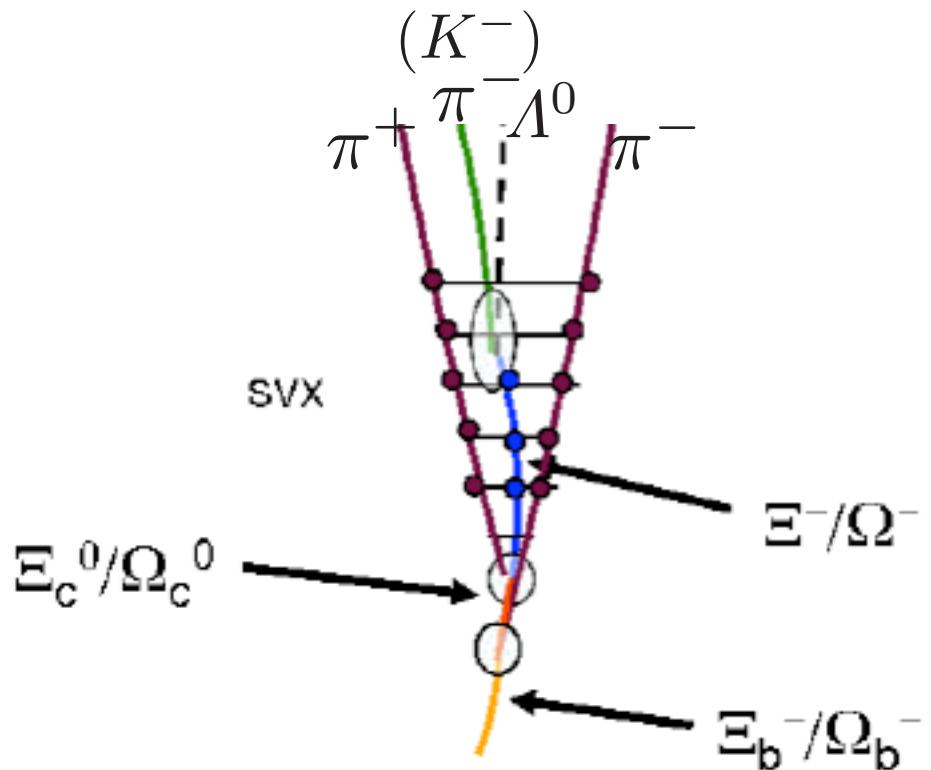
Candidates with  $J/\psi + \text{hadron}$  sample,  
 hadron =  $K_s^0, \Lambda^0, \Xi^-, \Omega^-$

State	Requirement
$J/\psi$	Si hits on $\mu^+, \mu^-$ , <b>VX fit with mass constraint</b>
hadron	<b>Convergent fit of 3 trks:</b> $\Xi^- \rightarrow \Lambda^0 (\rightarrow p\pi^-)\pi^-$ $(\Omega^- \rightarrow \Lambda^0 (\rightarrow p\pi^-)K^-)$
$J/\psi + \text{hadron}$	$p_{T(\text{tot})} > 6 \text{ GeV}/c$ $ct > 100 \mu\text{m}$



# Tracking Hyperons in Hadron Data Sample

- $p_T(\Xi^-/\Omega^-) > 1.5 \text{ GeV}/c$
- **long lifetimes**,  $c \cdot \tau = 4.9 / 2.5 \text{ cm}$ 
  - $\Xi^-/\Omega^-$  decay outward from beam line: leaving hits in Si detector.
  - $\Xi^-/\Omega^-$  subjected to VX fit with three tracks,
    - ◊ the VX point and momentum used as a search road for Si hits.
- the fit with Si hits improves  $d_0$  resolution,  $\sigma_{d_0} \lesssim 60 \mu\text{m}$

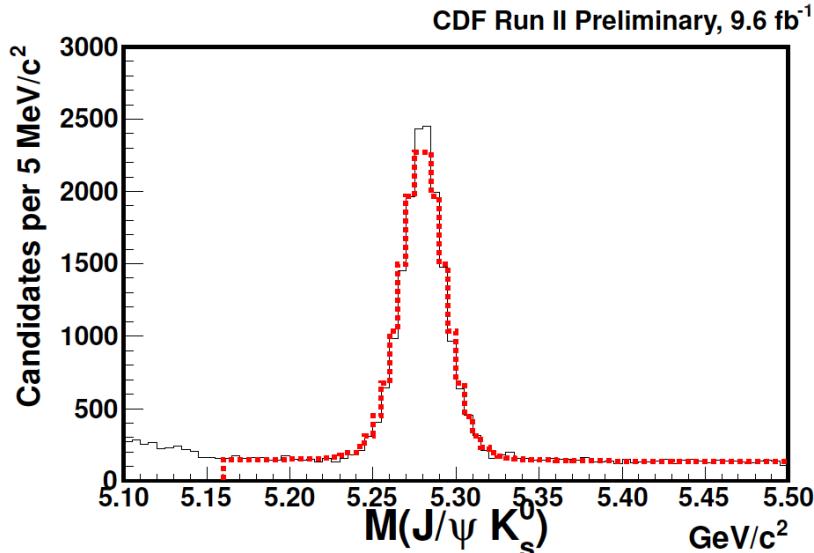


# Measurement Overview

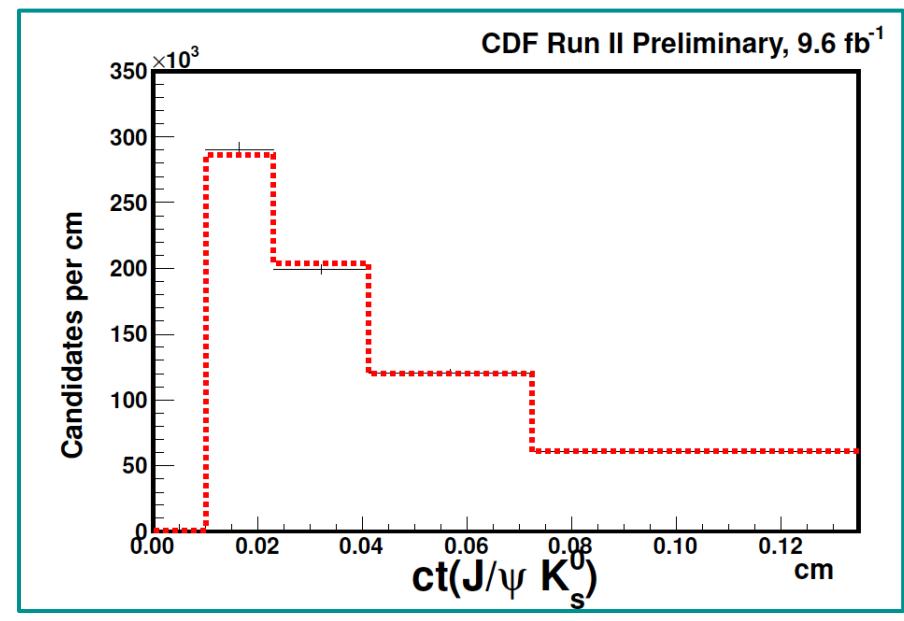
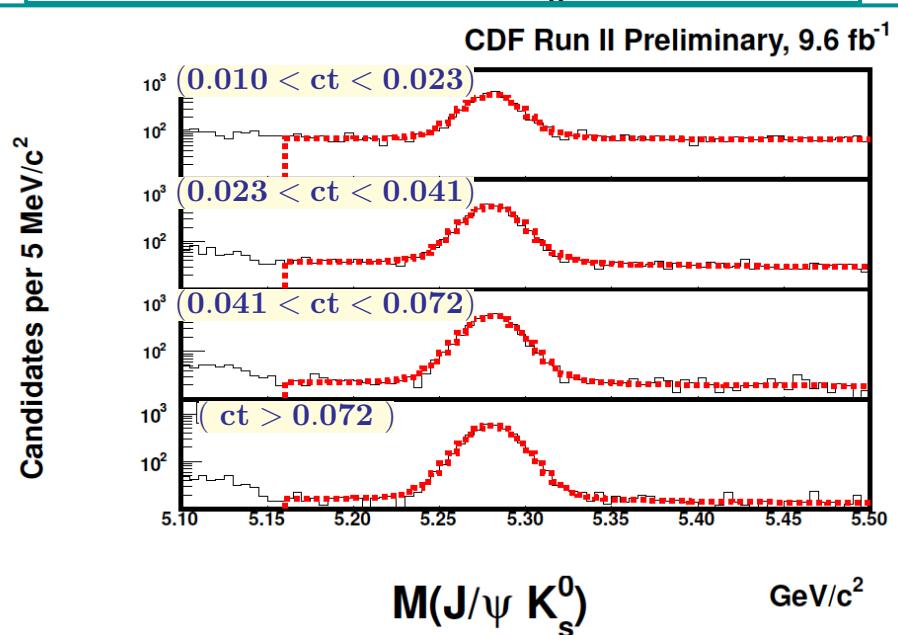
- Approach removes dependence on background decay time shape and resolution, which are hard to understand in low-statistics samples.
- The sample is binned in a proper decay time  $ct$ ,
- $ct$  bins chosen as to be nearly equally populated.
- (1) pass: We fit the unbinned mass distributions
  - unbinned fit finds the mass for the total sample and the yields per  $ct$  bin.
- (2) pass: the binned  $ct$  distribution is fitted.
- The modes,  $B^0 \rightarrow J/\psi K_S^0$ ,  $B^+ \rightarrow J/\psi K^+$  and  $B^0 \rightarrow J/\psi K^{*0}$  of known lifetime are used as calibration samples for the technique and systematics.

# B Meson Calibration Sample

## $B^0 \rightarrow J/\psi K_s^0$ (I)



- The di-muon trigger does not bias the  $ct$  distributions.
- Used to extract mean life and mass measurements.



# B Meson Calibration Sample

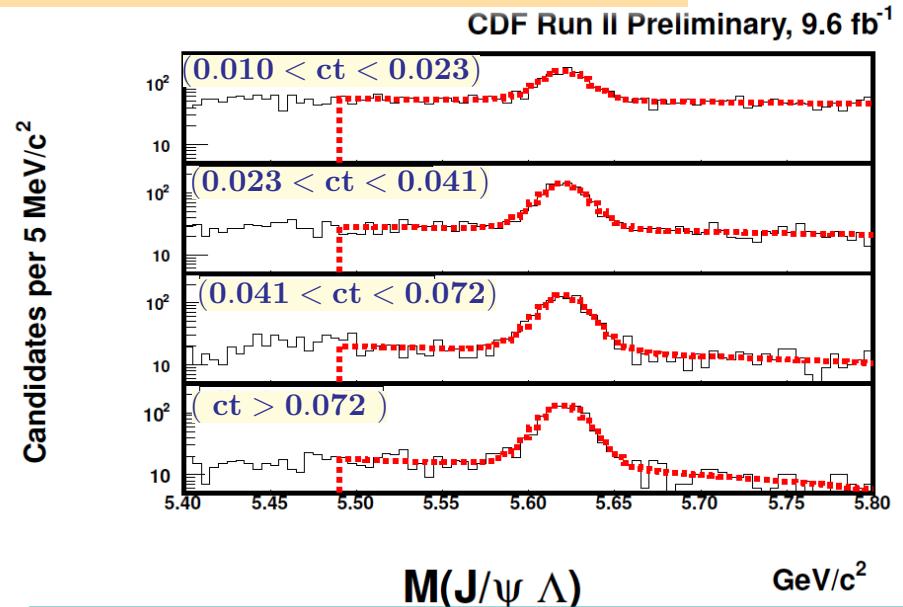
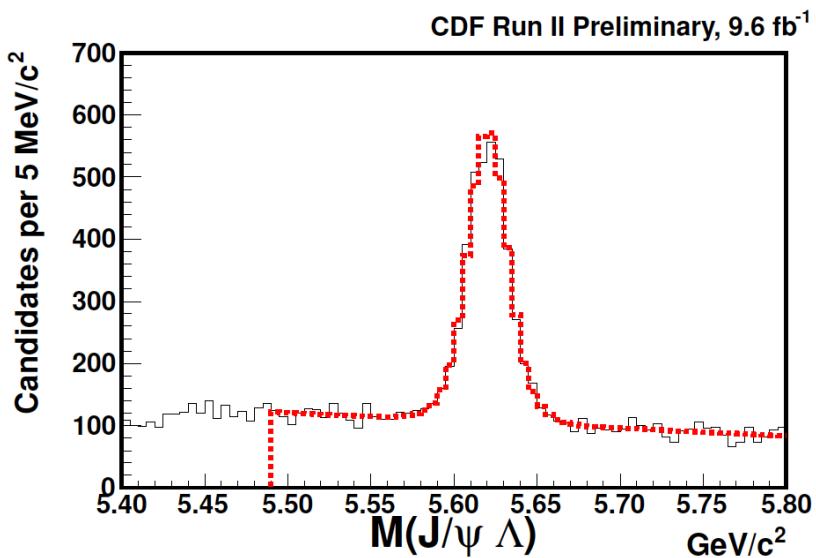
## $B^0 \rightarrow J/\psi K_s^0$ (II)

- *B* Meson Mass and Mean Life Measurements and Comparisons

Final State	Mass ( $\text{MeV}/c^2$ )		Mean life ( $\mu\text{m}$ )	
	Nominal	Difference	Nominal	Difference
$J/\psi K_s^0$	$5279.58 \pm 0.17$	$-0.5 \pm 0.2$	$455.4 \pm 2.1$	$1.2 \pm 6.1$
$\delta(ct)(\text{syst}) =$				$1.3\%$

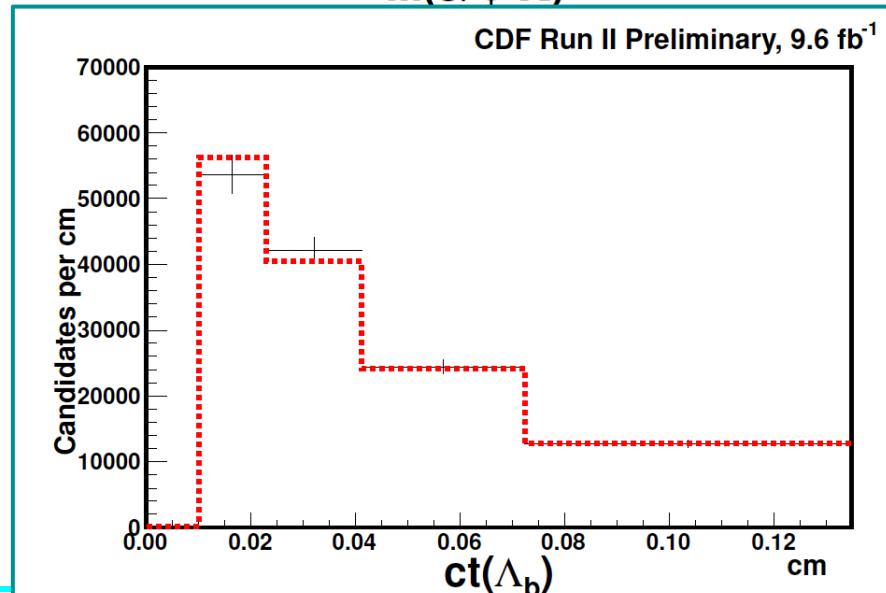
- *B* meson states reconstructed in fully exclusive modes with  $J/\psi \rightarrow \mu^+ \mu^-$ .
- Compare the subset of CDF Run II data not included into the nominal values (PDG).
- Reference to set  $\delta M(\text{syst})$ ,  $\delta(c\tau)(\text{syst})$ .

# $\Lambda_b^0 \rightarrow J/\psi \Lambda$



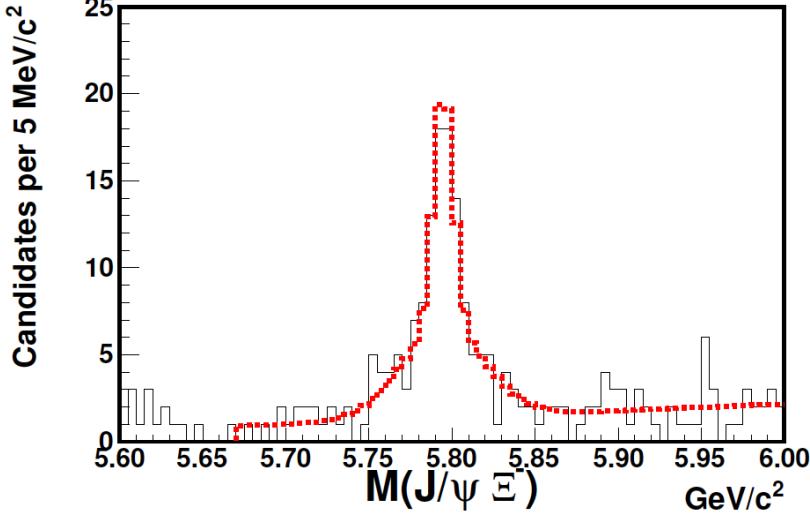
## Fits: Mass and Mean Life

Mode:	$\Lambda_b^0 \rightarrow J/\psi \Lambda^0$
$M$ , $\text{MeV}/\text{c}^2$	$5620.14 \pm 0.31(\text{stat})$
$c\tau$ , $\mu\text{m}$	$469.3 \pm 10.4(\text{stat})$
Fit Sample	$3018 \pm 121(\text{stat})$

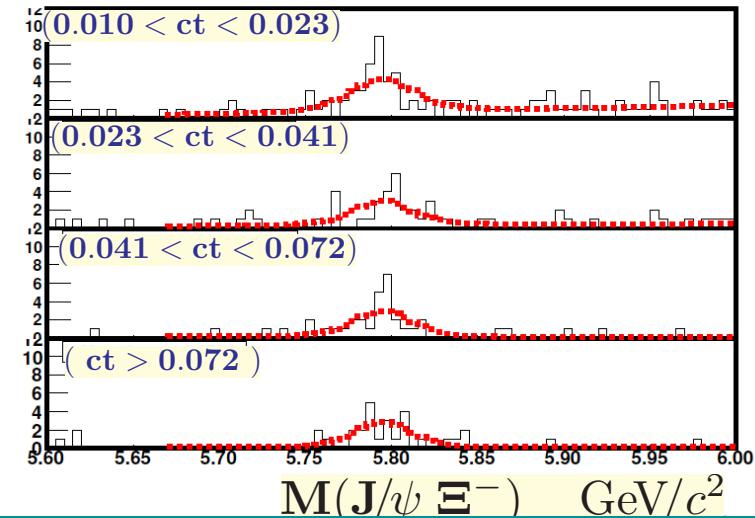




CDF Run II Preliminary, 9.6 fb<sup>-1</sup>



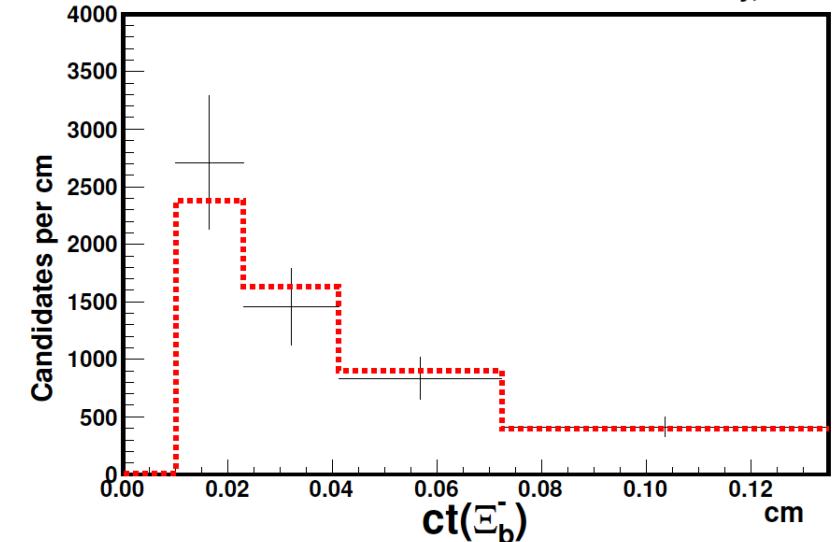
CDF Run II Preliminary, 9.6 fb<sup>-1</sup>

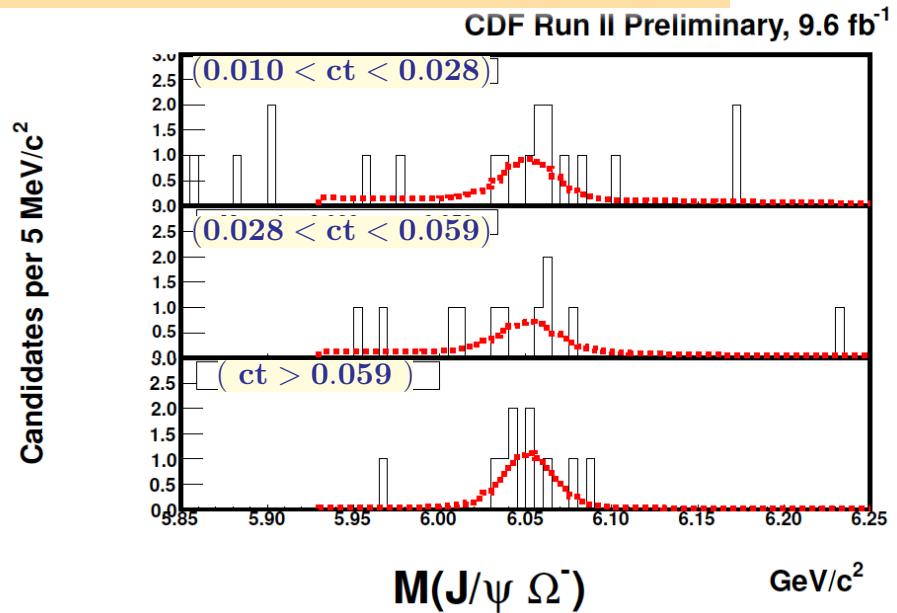
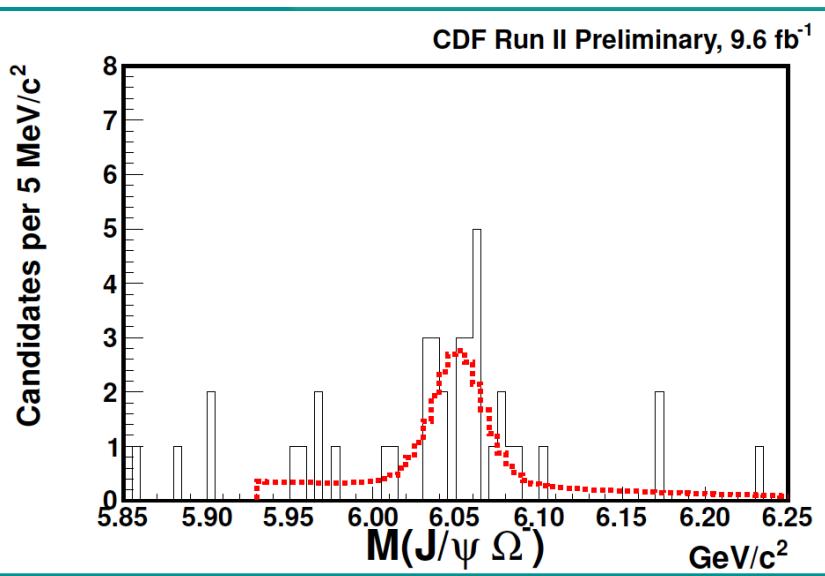


## Fits: Mass and Mean Life

<b>Mode:</b>	$\Xi_b^- \rightarrow J/\psi \Xi^-$
$M$ , $\text{MeV}/c^2$	$5794.1 \pm 0.2(\text{stat})$
$c\tau$ , $\mu\text{m}$	$409 \pm 45(\text{stat})$
<b>Fit Sample</b>	$114 \pm 17(\text{stat})$

CDF Run II Preliminary, 9.6 fb<sup>-1</sup>





## Fits: Mass and Mean Life

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**Mode:**  $\Omega_b^- \rightarrow J/\psi \Omega^-$

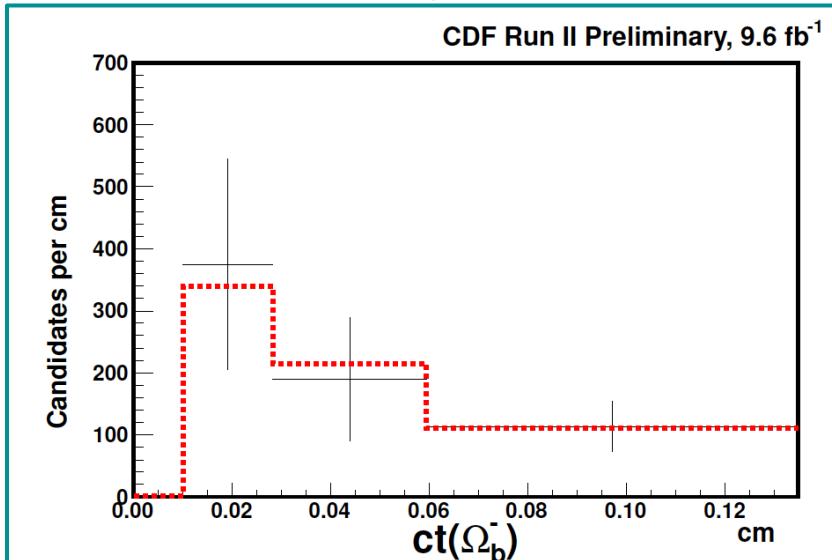
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**$M$ ,  $\text{MeV}/c^2$**   $6051.4 \pm 4.2(\text{stat})$

**$c\tau$ ,  $\mu\text{m}$**   $530^{+166}_{-122}(\text{stat})$

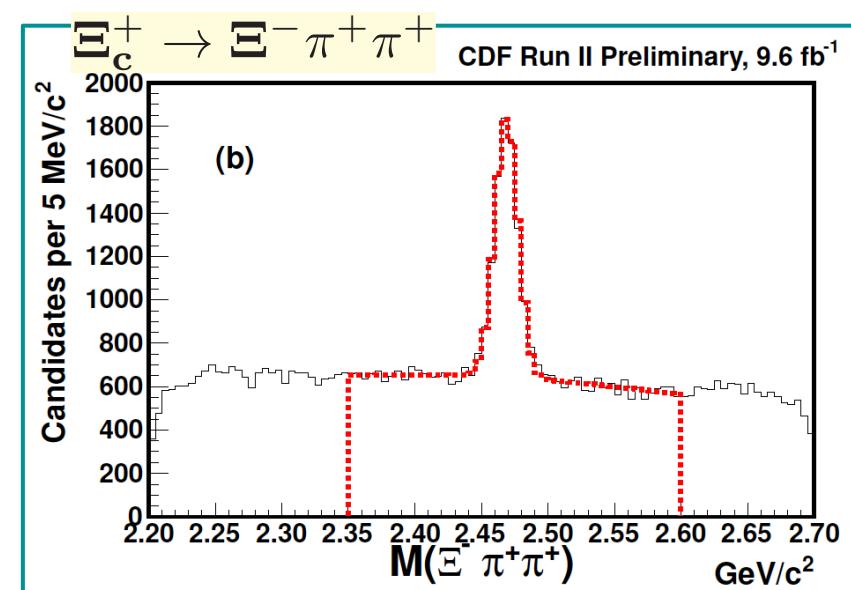
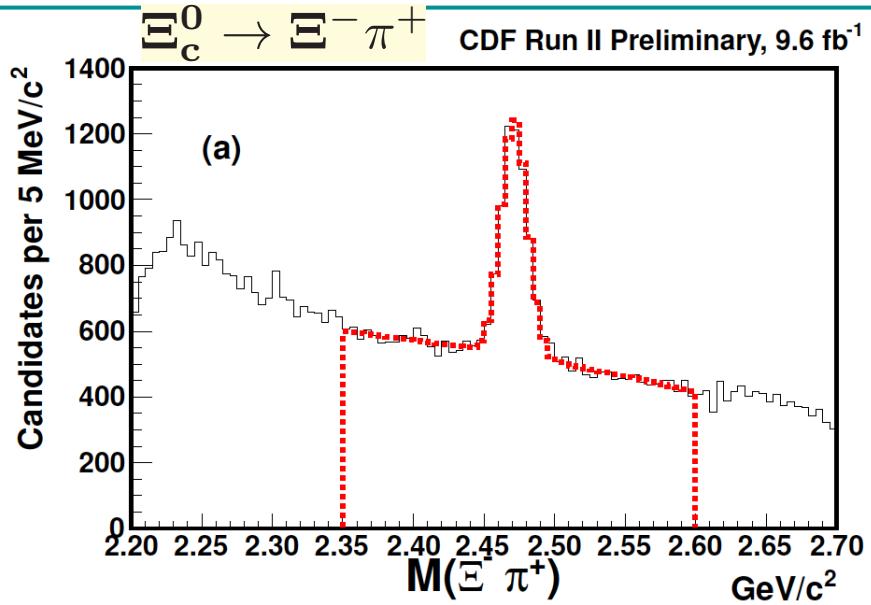
**Fit Sample**  $21 \pm 6(\text{stat})$

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# Charmed Single Strange Baryons: $\Xi_c^0 \rightarrow \Xi^- \pi^+$ and $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$

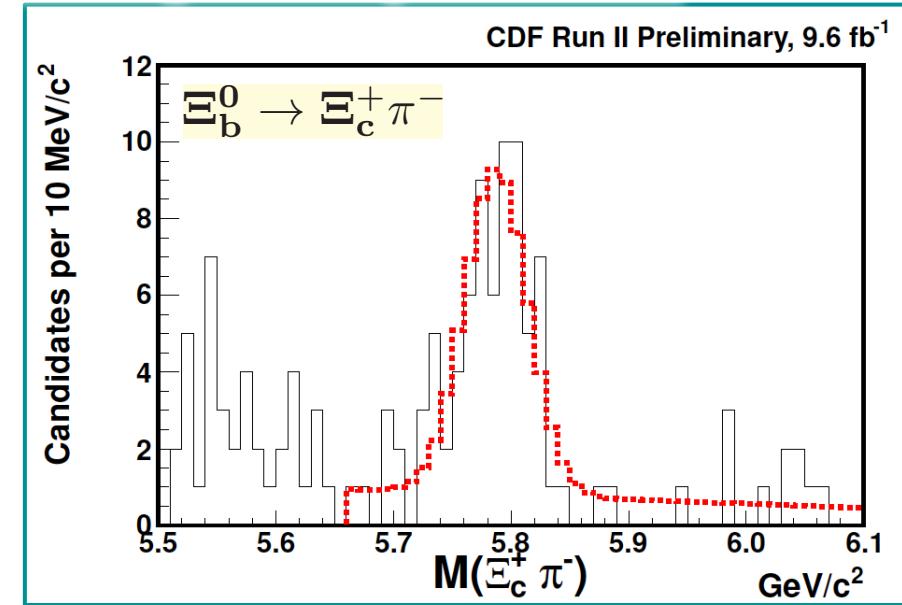
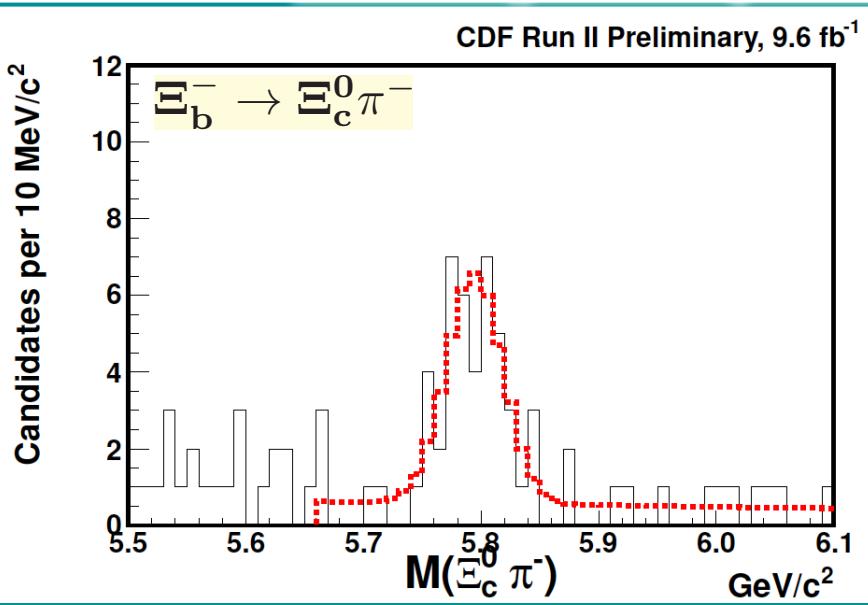
- Two Displaced Track Hadron Trigger: extract only mass measurements.



- $\Xi^-$  tracked with Si hits associated.

Results of the Unbinned LH Fit	
State	$M, \text{ MeV}/c^2$
$\Xi_c^0$	$2470.30 \pm 0.28(\text{stat})$
$\Xi_c^+$	$2467.19 \pm 0.17(\text{stat})$

# Bottom Single Strange Baryons: $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ and $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$



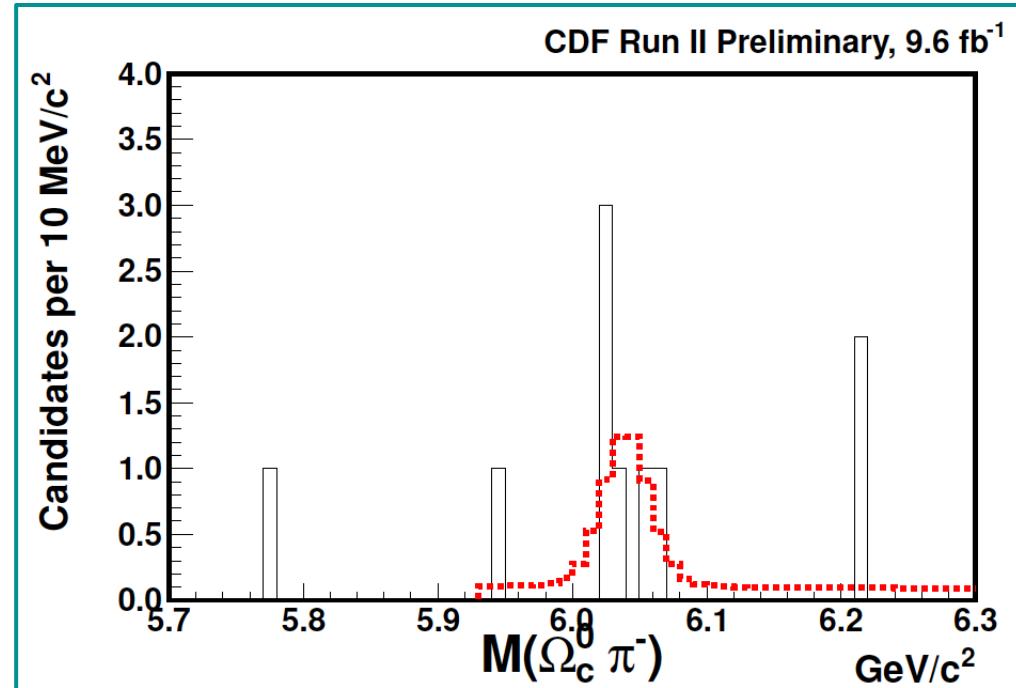
## Results of the Unbinned LH Fit

State	$M, \text{ MeV}/\text{c}^2$	Yield
$\Xi_c^0 \pi^-$	$5796.5 \pm 4.7(\text{stat})$	$58 \pm 10(\text{stat})$
$\Xi_c^+ \pi^-$	$5791.6 \pm 5.0(\text{stat})$	$36 \pm 7(\text{stat})$

# Bottom Double Strange Baryon:

$$\Omega_b^- \rightarrow \Omega_c^0 \pi^-$$

- Seen a narrow enhancement compatible with  $\Omega_b^-$ :
  - $\Omega_b^- \rightarrow \Omega_c^0 \pi^-$ ,  $\Omega_c^0 \rightarrow \Omega^- \pi^+$ ,  
 $\Omega^- \rightarrow \Lambda^0 K^-$
- $\Omega^-$  tracked with Si hits used
- Techniques are similar to  $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$
- Unbinned LH fit: single Gaussian plus linear background
- Significance estimate:
  - $\mathcal{H}_0$ : uniform distribution
  - generate  $\mathcal{H}_0$  statistical trials
  - fit with masses fixed to  $M \in (6046, 6054) \text{ MeV}/c^2$  (several known observed masses)



- **Experimental**  $2 \cdot \Delta(\ln \mathcal{L}) = 10.3$
- $p - \text{value} = 5.5 \cdot 10^{-4}$
- $\gtrsim 3.3\sigma$  of single sided Gaussian
- **Evidence of the Cabibbo favored decay with no color suppression.**

# Systematic Uncertainties on Mass

- Momentum scale:
  - The reference states reconstructed:  $J/\psi$ ,  $\psi(2S)$ ,  $\Upsilon(1S)$ ,  $\Upsilon(2S)$
  - Parameterize:  $M_{\text{ref}} - M_{PDG} = P_1(Q)$ ,
  - Find offsets for our measured masses.
- Mass resolution model:
  - Variations of fits of the  $B$  meson calibration signals:  $\delta(M) = 0.1 \text{ MeV}/c^2$  ,
  - assumed for all modes measured.
- Masses set for daughter particles used in mass constrained VX fits.
- Agreement with calibration  $B$ - meson signals.

# Systematic Uncertainties on Lifetime

- Identical to those of  $B$  mesons
- Take the most conservative:  
 $\Delta(c\tau)(B^0 \rightarrow J/\psi K_s^0)_{\text{PDG}} = (1.2 \pm 6.1) \mu\text{m}$
- Estimate:  $\delta(c\tau) = 6.1 \mu\text{m} / 455.4 \mu\text{m} \approx 1.3\%$

# *b*-Baryon Properties: Summary of Results

Final State	Mass (MeV/c <sup>2</sup> )	Mean life (ps)
$\Xi_c^0$	$2470.30 \pm 0.28(\text{stat}) \pm 0.35(\text{syst})$	-
$\Xi_c^+$	$2467.19 \pm 0.17(\text{stat}) \pm 0.35(\text{syst})$	-
$\Lambda_b$	$5620.14 \pm 0.31(\text{stat}) \pm 0.40(\text{syst})$	$1.565 \pm 0.035(\text{stat}) \pm 0.020(\text{syst})$
$\Xi_b^- (\text{J}/\psi \Xi^-)$	$5794.1 \pm 2.0(\text{stat}) \pm 0.40(\text{syst})$	$1.36 \pm 0.15(\text{stat}) \pm 0.02(\text{syst})$
$\Xi_b^- (\Xi_c^0 \pi^-)$	$5796.5 \pm 4.7(\text{stat}) \pm 0.95(\text{syst})$	-
$\Xi_b^0 (\Xi_c^+ \pi^-)$	$5791.6 \pm 5.0(\text{stat}) \pm 0.73(\text{syst})$	-
$\Omega_b^- (\text{J}/\psi \Omega^-)$	$6051.4 \pm 4.2(\text{stat}) \pm 0.50(\text{syst})$	$1.77^{+0.55}_{-0.41}(\text{stat}) \pm 0.02(\text{syst})$
$\Omega_b^- (\rightarrow \Omega_c^0 \pi^-)$	$6040 \pm 8(\text{stat}) \pm 2(\text{syst})$	-
<b>Evidence of <math>\gtrsim 3.3\sigma</math></b>		
$M(\Xi_c^0) - M(\Xi_c^+)$	$= 3.11 \pm 0.33(\text{stat}) \pm 0.07(\text{syst}) \text{ MeV/c}^2$	-
$M(\Xi_b^-) - M(\Xi_b^0)$	$= 2.5 \pm 5.4(\text{stat}) \pm 0.6(\text{syst}) \text{ MeV/c}^2$	-

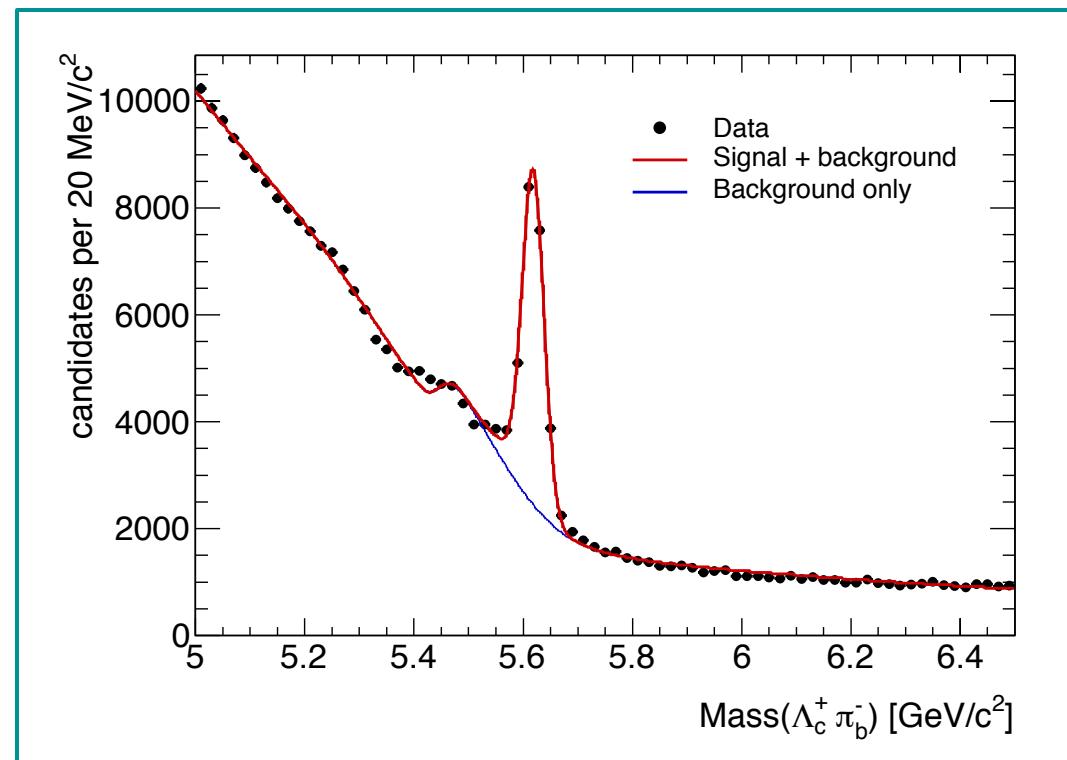
# **Bottom Baryon Resonant States**

# Search of Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Analysis Criteria (I)

$$\begin{aligned}\Lambda_b^{*0} &\rightarrow \Lambda_b^0 \pi_s^- \pi_s^+, \\ \Lambda_b^0 &\rightarrow \Lambda_c^+ \pi_b^-, \\ \Lambda_c^+ &\rightarrow p K^- \pi^+\end{aligned}$$

- $p_T(\Lambda_b^0) > 9 \text{ GeV}/c$
- **Soft pion**  $p_T(\pi_s^\pm)$ :
  - as low as  $200 \text{ MeV}/c$

Total CDF Luminosity of  $\int \mathcal{L} dt \approx 9.6 \text{ fb}^{-1}$   
collected by Two Displaced Track Trigger.



$N_{\Lambda_b^0} \approx 15400 \text{ cands.}$

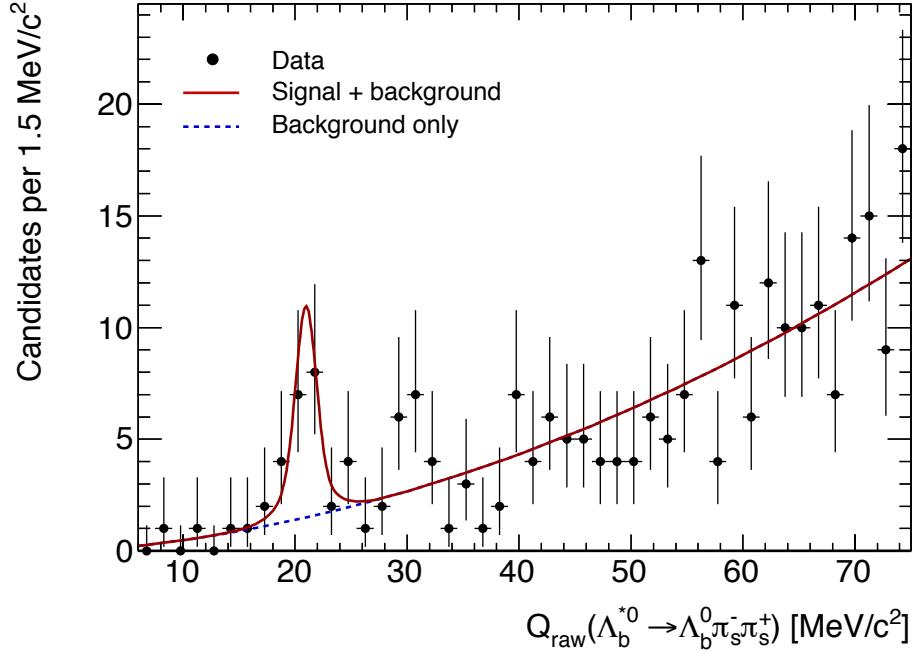
# Search of a Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Analysis Criteria (II)

## $\Lambda_b^{*0}$ Search

- search in the  $Q$ -value distribution:  
$$Q = m(\Lambda_b^0 \pi_s^- \pi_s^+) - m(\Lambda_b^0) - 2 \cdot m_\pi$$
- Use  $Q$ -value: effect of the  $\Lambda_b^0$  mass resolution is suppressed, most of the systematic uncertainties are reduced.
- search range  $Q \in (6 - 45) \text{ MeV}/c^2$ , motivated by the theor. predictions.

# Search of a Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Spectrum and Fit

$$\int \mathcal{L} dt \approx 9.6 \text{ fb}^{-1}$$



A narrow structure at  $Q \approx 21 \text{ MeV}/c^2$  is seen.

## Fit Model

- **Signal:** double Gaussian
- **Background:**  $\mathcal{P}^2(Q; C, b_1, b_2)$
- Generate stat. experiments of  $\mathcal{H}_0$  (background) and determine  $-2 \ln(\mathcal{L}_0/\mathcal{L}_1)$  per trial
  - $p = 2.3 \cdot 10^{-4}$  or  $3.5\sigma$

$\Lambda_b^{*0}$	
Parameters	Value
$Q$ , $\text{MeV}/c^2$	$20.96 \pm 0.35$
$N$ , evts	$17.3^{+5.3}_{-4.6}$

# Search of a Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Syst. Uncertainties (I)

## Momentum Scale

- The uncertainty on the  $Q$ -value due to low- $p_T$   $\pi_s^\pm$  tracks.
- Use large experimental calibration sample of  $D^{*+} \rightarrow D^0 \pi_s^+$
- Compare  $Q(D^{*+})$  signal position with PDG and find the  $Q$  value adjustment for  $\Lambda_b^{*0} \rightarrow \Lambda_b^0 \pi_s^- \pi_s^+$ :  $\Delta Q = -0.28 \text{ MeV}/c^2$ .
- set 100% for syst.:  $-0.28 \pm 0.28 \text{ MeV}/c^2$ .

# Search of a Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Syst. Uncertainties (II)

Systematics Uncertainties		
Source	Value, MeV/ $c^2$	Comment
Momentum scale	$\pm 0.28$	propagated from high statistics calibration $D^{*+}$ sample; 100% of the found adjustment value.
Signal model	$\pm 0.11$	MC underestimates the resolution; choice of the model's parameters
MC resolution stat. uncertainty	$\pm 0.012$	finite MC sample size induces the stat. uncertainty of the shape parameters.
Background model	$\pm 0.03$	consider 3-rd, 4-th power polynomials
<b>Total:</b>	<b><math>\pm 0.30</math></b>	<b>added in quadrature</b>

# Search of a Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Results

Value	MeV/c <sup>2</sup>
$Q$	$20.68 \pm 0.35$ (stat) $\pm 0.30$ (syst)
$\Delta M$	$299.82 \pm 0.35$ (stat) $\pm 0.30$ (syst)
$M(\Lambda_b^{*0})$	$5919.22 \pm 0.35$ (stat) $\pm 0.30$ (syst) $\pm 0.60$ ( $\Lambda_b^0$ )
$M(\Lambda_b^{*0})$	$5919.22 \pm 0.76$
$M(\Lambda_b^{*0})(\text{LHCb})$	$5919.77 \pm 0.08$ (stat) $\pm 0.02$ (syst) $\pm 0.66$ ( $\Lambda_b^0$ )

- $M(\Lambda_b^0)$  from updated PDG (live).
- Result is closest to the calculation based on  $1/m_Q$ ,  $1/N_c$  expansions, Z. Aziza Baccouche et al., PLB 514, 346 (2001).
- Consistent with the higher state  $\Lambda_b^{*0}(5920)$  observed by LHCb, PRL 109, 172003 (2012).

# $\Lambda_b^{*0}$ in CDF data : Summary

Phys. Rev. D 88, 071101(R) (2013)  
[arXiv:1308.1760 [hep-ex]].

- We conduct a search for the  $\Lambda_b^{*0} \rightarrow \Lambda_b^0 \pi^- \pi^+$  resonance state in its Q-value spectrum.
- A narrow structure is identified at  $5919.22 \pm 0.76 \text{ MeV}/c^2$  mass with a significance of  $3.5\sigma$ .
- This signal is attributed to the orbital excitation of the bottom baryon  $\Lambda_b^0$  and confirms similar findings in proton-proton collisions (LHCb).

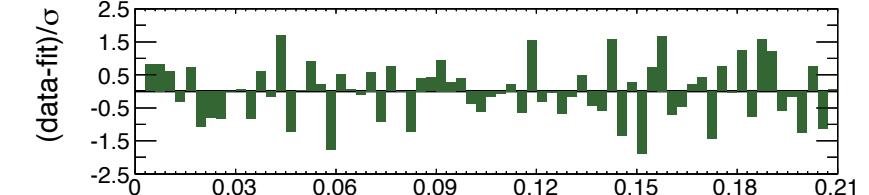
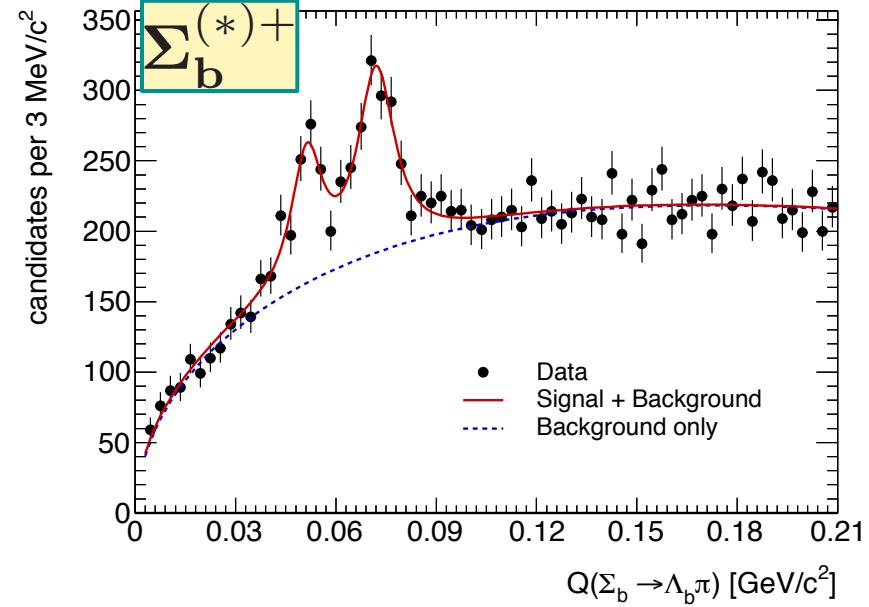
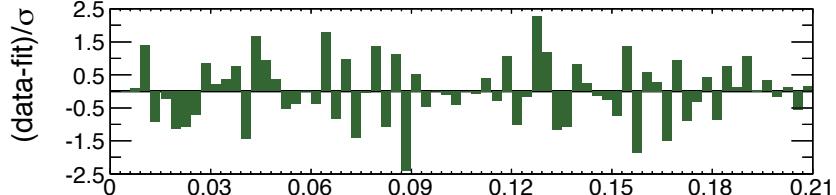
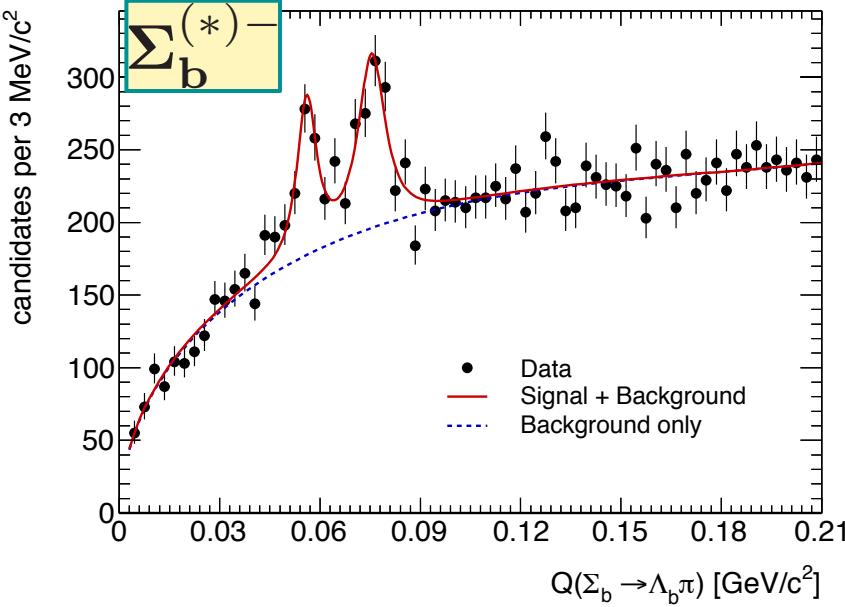
# Earlier Results on Bottom Baryon Resonances: $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$

$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi_{soft}^{\pm}, \Lambda_b^0 \rightarrow \Lambda_c^+ \pi_b^-, \Lambda_c^+ \rightarrow p K^- \pi^+$$

Phys. Rev. D 85, 092011 (2012)  
 [arXiv:1112.2808 [hep-ex]].

First Observation by CDF:  
 Phys. Rev. Lett. 99, 202001 (2007)  
 [arXiv:0706.3868 [hep-ex]]].

$$\int \mathcal{L} dt \approx 6 \text{ fb}^{-1}$$



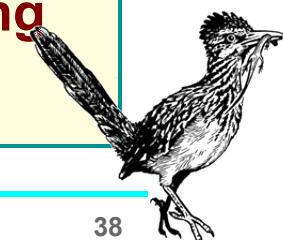
# Measurement of Bottom Baryons $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ : Results (II)

**Summary of the final results. The first uncertainty is statistical and the second is systematic.**

State	$Q$ value, MeV/ $c^2$	Absolute mass $m$ , MeV/ $c^2$	Natural width $\Gamma$ , MeV/ $c^2$
$\Sigma_b^-$	$56.2^{+0.6+0.1}_{-0.5-0.4}$	$5815.5^{+0.6}_{-0.5} \pm 1.7$	$4.9^{+3.1}_{-2.1} \pm 1.1$
$\Sigma_b^{*-}$	$75.8 \pm 0.6^{+0.1}_{-0.6}$	$5835.1 \pm 0.6^{+1.7}_{-1.8}$	$7.5^{+2.2+0.9}_{-1.8-1.4}$
$\Sigma_b^+$	$52.1^{+0.9+0.1}_{-0.8-0.4}$	$5811.3^{+0.9}_{-0.8} \pm 1.7$	$9.7^{+3.8+1.2}_{-2.8-1.1}$
$\Sigma_b^{*+}$	$72.8 \pm 0.7^{+0.1}_{-0.6}$	$5832.1 \pm 0.7^{+1.7}_{-1.8}$	$11.5^{+2.7+1.0}_{-2.2-1.5}$
Isospin mass splitting, MeV/ $c^2$			
$m(\Sigma_b^+) - m(\Sigma_b^-)$		$-4.2^{+1.1}_{-1.0} \pm 0.1$	
$m(\Sigma_b^{*+}) - m(\Sigma_b^{*-})$		$-3.0^{+1.0}_{-0.9} \pm 0.1$	

# Conclusions

- Ground state  $b$ -baryon properties with full CDF data set
  - Based on  $J/\psi$  trigger, the largest possible sample: mass and mean life time measurements
    - systematic uncertainties controlled by the precisely measured  $B$  mesons in the similar modes
    - the results supersede previous CDF measurements, consistent with recent LHCb ones.
  - Based on hadron trigger sample:
    - confirmed  $\Xi_b^0$ , isospin partner of  $\Xi_b^-$ , the only observation to date.
    - mass splitting within  $(\Xi_b^0, \Xi_b^-)$  isospin doublet
    - mass splitting within  $(\Xi_c^+, \Xi_c^0)$  isospin doublet
    - first evidence for the decay,  $\Omega_b^- \rightarrow \Omega_c^0 \pi^-$ .
- Evidence for a  $b$ -baryon resonance  $\Lambda_b^{*0}$  in CDF
  - confirmation of the LHCb recent observation
- $b$ -baryon resonance states:  $\Sigma_b^{+-}$  and  $\Sigma_b^{*+-}$  width, mass and isospin mass splitting measurements
- During last two decades, CDF Collaboration was leading the research and made a remarkable contribution to the spectroscopy of bottom baryon states.



# **Backup Slides**

# Multiplets of *b*-Baryons (I)

State	Quarks	$J^P$	$(I, I_3)$
<i>S-wave Bottom Baryon States</i>			
$\Lambda_b^0$	$b[ud]$	$(1/2)^+$	$(0, 0)$
$\Sigma_b^+$	$buu$	$(1/2)^+$	$(1, +1)$
$\Sigma_b^0$	$b\{ud\}$	$(1/2)^+$	$(1, 0)$
$\Sigma_b^-$	$bdd$	$(1/2)^+$	$(1, -1)$
$\Sigma_b^{*+}$	$buu$	$(3/2)^+$	$(1, +1)$
$\Sigma_b^{*0}$	$b\{ud\}$	$(3/2)^+$	$(1, 0)$
$\Sigma_b^{*-}$	$bdd$	$(3/2)^+$	$(1, -1)$
$\Xi_b^-$	$b[sd]$	$(1/2)^+$	$(1/2, -1/2)$
$\Xi_b^{'-}$	$b\{sd\}$	$(1/2)^+$	$(1/2, -1/2)$
$\Xi_b^{*-}$	$b\{sd\}$	$(3/2)^+$	$(1/2, -1/2)$
$\Xi_b^0$	$b[su]$	$(1/2)^+$	$(1/2, +1/2)$
$\Xi_b^{'0}$	$b\{su\}$	$(1/2)^+$	$(1/2, +1/2)$
$\Xi_b^{*0}$	$b\{su\}$	$(3/2)^+$	$(1/2, +1/2)$
$\Omega_b^0$	$bss$	$(1/2)^+$	$(0, 0)$
<i>Orbital P- wave Bottom Baryon States</i>			
$\Lambda_b^{*0}$	$b[ud]$	$(1/2)^-$	$(0, 0)$
$\Lambda_b^{*0}$	$b[ud]$	$(3/2)^-$	$(0, 0)$

→ **Bottom baryon  $\Lambda$ - and  $\Sigma$ - states.**

- **Heavy Baryon quark content:**  $Q q_1 q_2$
- The  $[q_1 q_2]$  denotes a pair *antisymmetric* in flavor and spin.
- The  $\{q_1 q_2\}$  denotes a pair *symmetric* in flavor and spin.

# QCD Phenomenology of Heavy Quark Baryons (II)

- **$S$ -wave states,  $L_{qq} = 0$**

- **Total  $q_1 q_2$  spin,  $S_{qq}$ :**

$$\frac{1}{2}^+ \otimes \frac{1}{2}^+ \rightarrow 0^+ \oplus 1^+$$

- $\frac{1}{2}^+ \otimes 0^+ \rightarrow \frac{1}{2}^+$  corresponds to singlet

$$\Lambda_b^0 \equiv b[ud], S_b^P = \frac{1}{2}^+, S_{[ud]}^P = 0^+, J^P = \frac{1}{2}^+$$

- $\frac{1}{2}^+ \otimes 1^+ \rightarrow \frac{1}{2}^+ \oplus \frac{3}{2}^+$  correspond to two  
 $\Sigma_b^{(*)} \equiv b\{qq\}, S_b^P = \frac{1}{2}^+, S_{\{qq\}}^P = 1^+$

- **two isospin  $I = 1$  triplets:**

$\Sigma_b^-$ ,  $\Sigma_b^0$ ,  $\Sigma_b^+$  with  $J^P = \frac{1}{2}^+$  and

$\Sigma_b^{*-}$ ,  $\Sigma_b^{*0}$ ,  $\Sigma_b^{*+}$  with  $J^P = \frac{3}{2}^+$

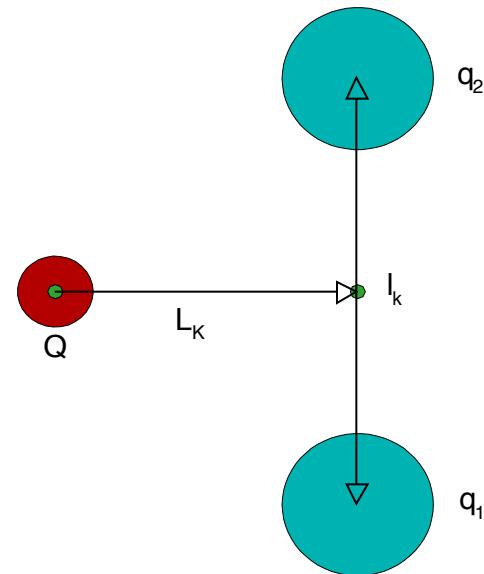
- **$P$ -wave states, orbitally excited,  $L_{qq} = 1$**

- **Light diquark:**  $S_{[ud]}^P = 0^+$ ,  $L_{[ud]}^P = 1^-$

- $\frac{1}{2}^+ \otimes (0^+ \otimes 1^-) \rightarrow \frac{1}{2}^- \oplus \frac{3}{2}^-$   
**corresponds to two  $I = 0$  singlets,**

$$\Lambda_b^{*0} \equiv b[ud], J^P = \frac{1}{2}^- \text{ and } J^P = \frac{3}{2}^-$$

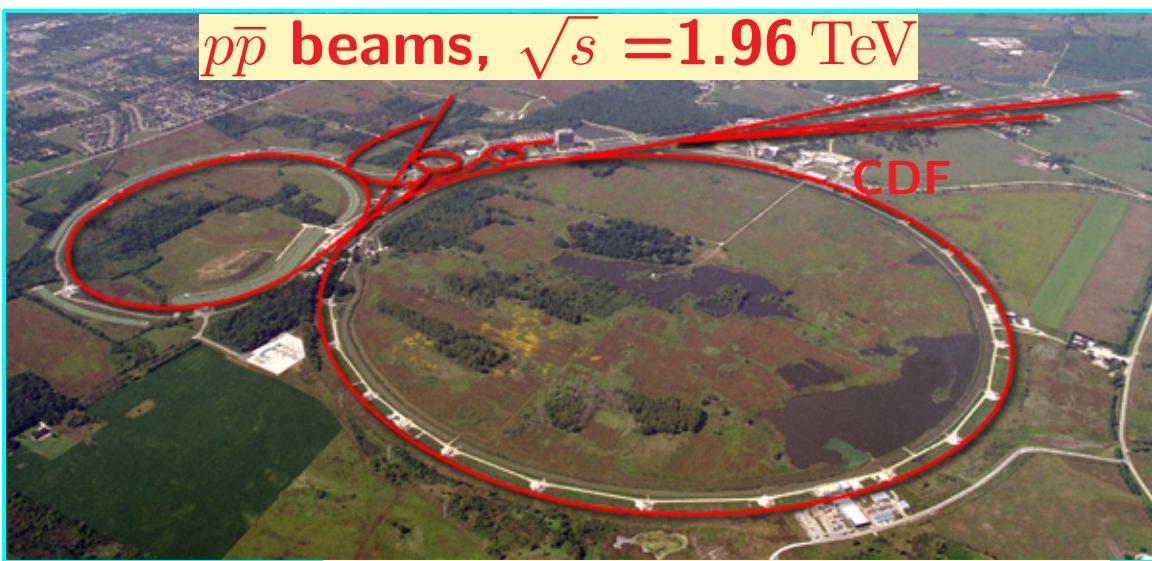
**$Qq_1q_2$  System: Orbital Angular Momenta.**



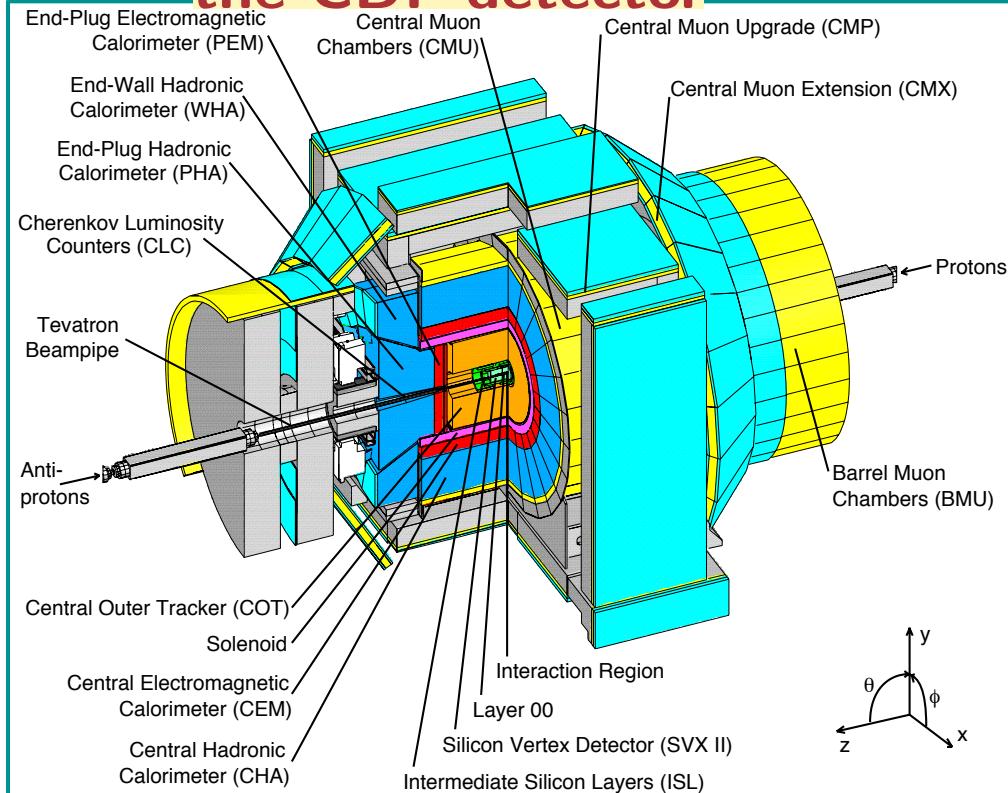
$$\begin{aligned} \Rightarrow \vec{J}_{qq} &= \vec{S}_{qq} + \vec{L}_{qq} \\ \Rightarrow \vec{J}_{Qqq} &= \vec{S}_Q + \vec{J}_{qq} \end{aligned}$$

# CDF Detector at proton – anti-proton Collider Tevatron (I)

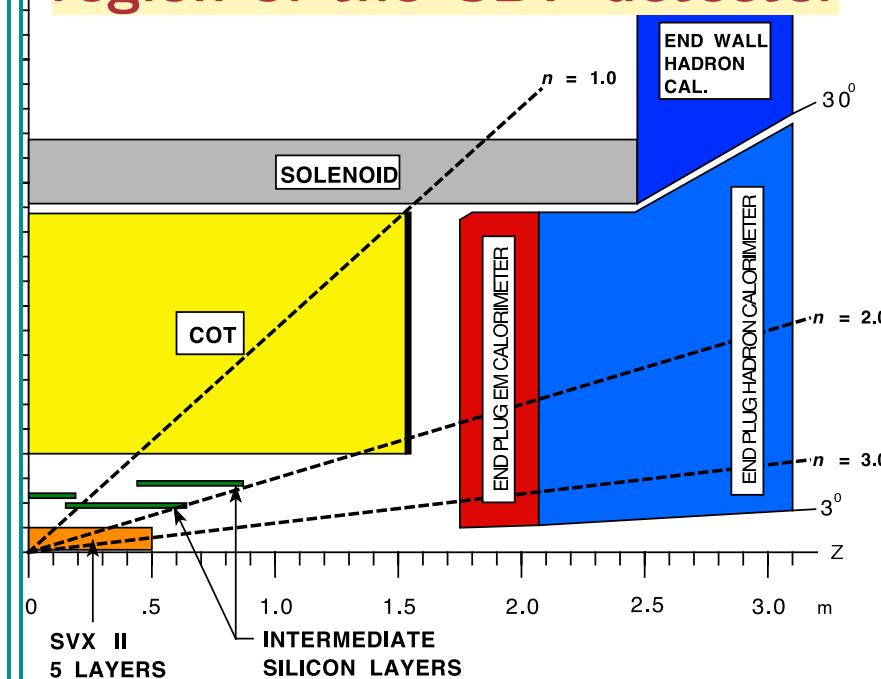
$p\bar{p}$  beams,  $\sqrt{s} = 1.96$  TeV



Isometric view of the CDF detector



Side view of the central region of the CDF detector



# CDF Detector at proton – anti-proton Collider Tevatron (III)

## CDF Main Drift Chamber 1/6 section of the COT end plate

T. Affolder et al / Nuclear Instruments and Methods in Physics Research A 526 (2004) 249–299

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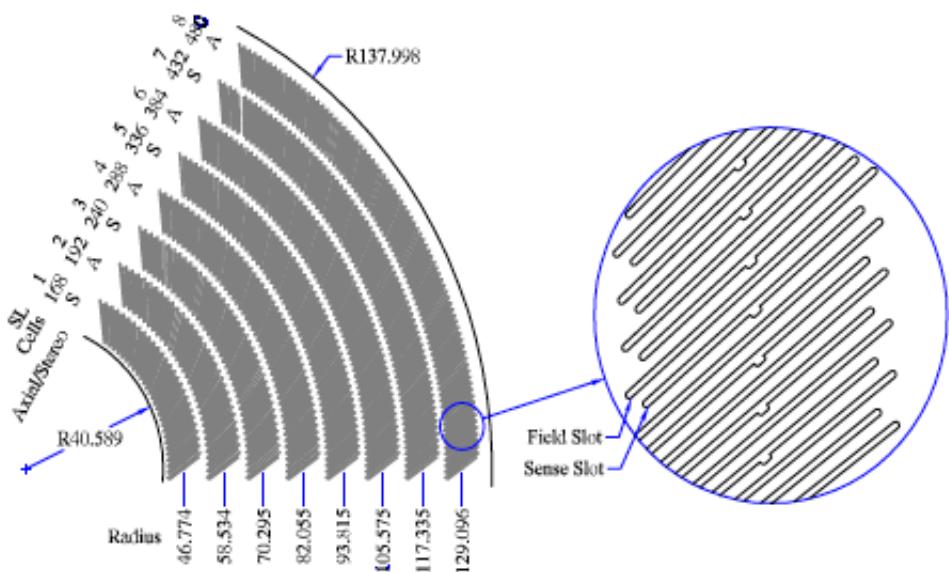
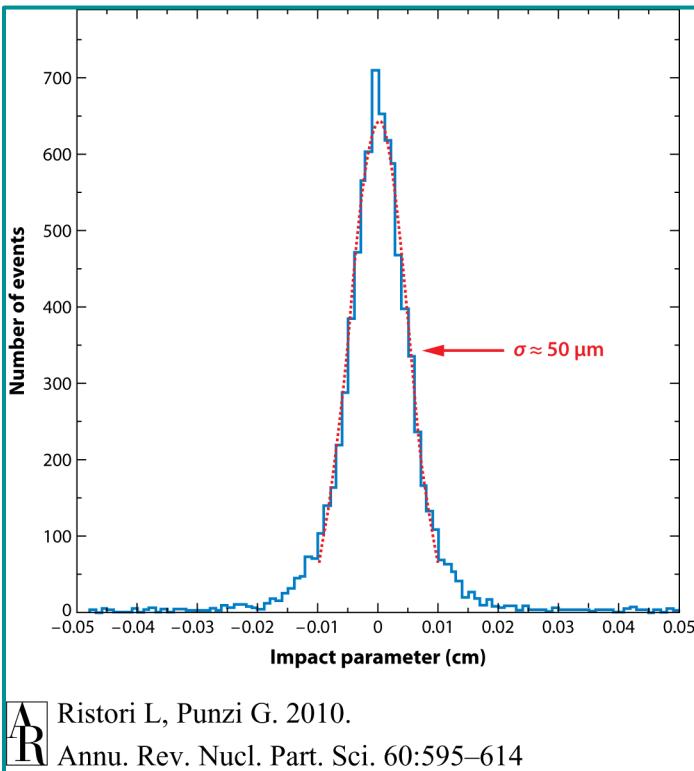


Fig. 2. 1/6 section of the COT end plate. For each superlayer is given the total number of supercells, the wire orientation (axial or stereo), and the average radius. The enlargement shows the sense and field slot geometry in detail. Dimensions are in cm.

- Axial magnetic field: 1.4 T
- Large open cell cylindrical drift chamber, the central outer tracker, COT
- (8 SuperLayers along r)  $\times$  (12 sense wires / SL) = 96 sense wire layers along r
- The combined, L00 + SVX-II + ISL + COT, track  $p_T$  resolution:  $\sigma(p_T)/p_T^2 \approx 0.07\%$ ,  $p_T$  in GeV/c

# Triggering on Heavy Flavors with Displaced Tracks (II)

- Level 1: COT hits processed by the extremely fast tracker (XFT) trigger
  - $(p_T, \phi)$  per track,  $\sim 5\mu s$
  - low precision for  $d_0$  measurements
- Level 2: I.P. reconstructed by Si Vertex Trigger (SVT) processors (VLSI technology)
  - $(p_T, \phi)$  from XFT are fed into SVT
  - SVT uses 5 concentric SVXII layers (0–4), with strips parallel to the beam ( $z$  coordinate)
  - produce precise enough  $d_0$  within  $\sim 20\mu s$
  - Excellent SVT resolution of  $d_0$ :  
 $\sigma_{d_0} \approx 50\mu m$ , with  $\sigma_{beam} \approx 32\mu m$  included
- Level 3: full reconstruction of the event with all detector information, confirmation of Level 2 (SVT)



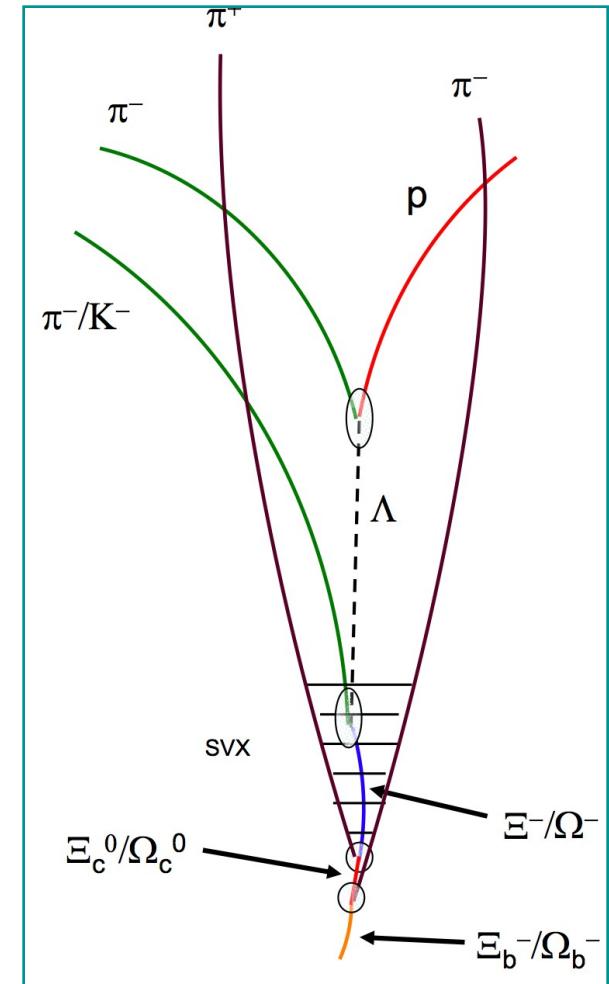
Ristori L, Punzi G. 2010.  
Annu. Rev. Nucl. Part. Sci. 60:595–614

# Bottom Baryons Reconstruction:

$\Xi_b^- \rightarrow \Xi_c^0 \pi^-$ ,  $\Omega_b^- \rightarrow \Omega_c^0 \pi^-$

Reconstruction in the Hadronic  
Sample collected by Two Displaced  
Track Trigger

State	Requirement
$\Xi_c^0$	$M(\Xi^- \pi^+) = (2471 \pm 30) \text{ MeV}/c^2$
$\Xi_c^+$	$M(\Xi^- \pi^+ \pi^+) = (2469 \pm 25) \text{ MeV}/c^2$
$\pi^+$	$2\sigma_{ct} < ct(\Xi_c) < 3 \cdot c\tau_0 + 2\sigma_{ct}$
$\pi^-$	$p_T(\pi^+) > 2 \text{ GeV}/c$ , $ d_0  > 100 \mu\text{m}$ <b>Si hits required to get <math>\sigma_{d_0} \approx 40 \mu\text{m}</math> contributes to hadron trigger</b> $p_T(\pi^-) > 2 \text{ GeV}/c$ , $ d_0  > 100 \mu\text{m}$ <b>Si hits required, <math>\sigma_{d_0} \approx 40 \mu\text{m}</math> contributes to hadron trigger</b> Chrg. opp. to the $\Lambda^0$ bar. numb. Satisfies VX fit with $\Xi^-$ track $ct > 100 \mu\text{m}$ $ d_0  < 100 \mu\text{m}$
$\Xi_c^- + \pi^+ (+\pi^+)$	track reconstructed with Si hits decay products found and reconstructed in main drift chamber
$\Xi^-$ $\Lambda^0$ , $\Xi^-$ , $\Omega^-$	



# Mass and Mean Life Fitter

- Unbinned invariant mass distributions fitted by minimization of  $-2 \cdot \ln(\mathcal{L})$  and giving  $m_0$  and number of events per  $ct$  bin

$$\mathcal{L} = \prod_j^{N_b} \prod_i^{N_j} \mathcal{P}_i^j$$

$$\begin{aligned} \mathcal{P}_i^j &= f_s^j \cdot G(m_i; m_0, s_1 \sigma_i) \\ &+ (1 - f_s^j) \cdot P_n(m_i; p_1^j, p_2^j, \dots, p_n^j) \end{aligned}$$

$N_b$  = numb. of  $ct$  bins chosen for the fit

$N_j$  = numb. of evts. in bin  $j$

$m_0$  = average mass over total sample

$f_s^j$  = fraction of the signal w.r.t. backgr.  
in bin  $j$  (of  $ct$ )

$s_1$  = common mass resolution scale factor

$\sigma_i$  = mass uncertainty calculated per event  $i$

$P_n(m_i; p_1^j, p_2^j, \dots, p_n^j)$  = norm.,  $p_0 = 1$ , polyn.

- **Fit in two passes is insensitive to the background "proper decay time" and background "resolution" terms.**

- binned proper decay time  $ct$  distributions comparing fitted fractional occupancies per  $ct$  bin with the ones calculated according to proper decay time model: extend the  $\mathcal{L}$  of the fitter:

$$R_j = \frac{f_s^j \cdot N_j}{\sum_k^{N_b} (f_s^k \cdot N_k)}$$

$$\begin{aligned} \mathcal{L} &= \prod_j^{N_b} G(R_j, \sigma_{R_j}; w_j(c\tau_0, \sigma_{ct})) \\ &\times \prod_i^{N_j} \mathcal{P}_i^j \end{aligned}$$

- two passes: (1) unbinned LH fit finds mass and yields per  $ct$  bin, (2) fit binned  $ct$  distribution.
- $ct > 100 \mu\text{m}$ , to not consider this first bin. binned  $ct$  distribution.
- select  $ct$  bins to equally populate bins based on a prior knowledge of mean life.

# Systematic Uncertainties (II)

- Mass Systematic Uncertainty Contributions

Effect	Uncertainty ( $\text{MeV}/c^2$ )										
	$\Xi_c^0$	$\Xi_c^+$	$B^0$	$J/\psi K^{0*}$	$J/\psi K_s^0$	$\Lambda_b$	$J/\psi \Xi^-$	$\Xi_b^-$	$\Xi_b^0$	$J/\psi \Omega^-$	$\Omega_b^0 \pi^-$
$\Xi_c^{0,+}$ mass	-	-	-	-	-	-	-	0.8	0.6	-	1.7
$\Omega^-$ mass	-	-	-	-	-	-	-	-	-	0.29	0.29
Mom. Scale	0.35	0.35	0.42	0.45	0.40	0.40	0.50	0.40	0.40	0.40	0.55
Unc. Model	0.05	0.05	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	0.35	0.35	0.42	0.45	0.40	0.40	0.95	0.73	0.50	0.50	1.8

- $J/\psi$ ,  $\psi(2S)$ ,  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  used to set the mass scale offsets
- Offset is parameterized against  $Q$ -value
- Checkout the method with  $B^0$  measurements: compatible

- Mean Life Measurement Systematic Uncertainties

- Identical to those of  $B$  mesons
- Take the most conservative:
- $\Delta(c\tau)(B^0 \rightarrow J/\psi K_s^0)_{\text{PDG}} = (1.2 \pm 6.1) \mu\text{m}$
- Estimate:  $\delta(c\tau) = 6.1 \mu\text{m}/455.4 \mu\text{m} \approx 1.3\%$

# *b*-Baryon Properties: Comparison to LHCb

Process		Mass(MeV/c <sup>2</sup> )	Mean Life(ps)
$\Lambda_b \rightarrow J/\psi \Lambda$	CDF	$5620.14 \pm 0.31(\text{stat}) \pm 0.40(\text{syst})$	$1.565 \pm 0.035(\text{stat}) \pm 0.020(\text{syst})$
	LHCb	$5619.53 \pm 0.13(\text{stat}) \pm 0.45(\text{syst})$	$1.482 \pm 0.018(\text{stat}) \pm 0.012(\text{syst})$
$\Xi_b^- \rightarrow J/\psi \Xi^-$	CDF	$5794.1 \pm 2.0(\text{stat}) \pm 0.4(\text{syst})$	$1.36 \pm 0.15(\text{stat}) \pm 0.02(\text{syst})$
	LHCb	$5795.8 \pm 0.9(\text{stat}) \pm 0.4(\text{syst})$	–
$\Omega_b^- \rightarrow J/\psi \Omega^-$	CDF	$6051.4 \pm 4.2(\text{stat}) \pm 0.5(\text{syst})$	$1.77^{+0.55}_{-0.41}(\text{stat}) \pm 0.020(\text{syst})$
	LHCb	$6046.0 \pm 2.2(\text{stat}) \pm 0.5(\text{syst})$	–

- The syst. uncertainties are very similar!
- CDF has  $\simeq 2 \times$  larger stat. uncertainties.

# QCD Phenomenology of Heavy Quark Baryons : $\Lambda_b^*$ predictions

⇒ Mass Predictions,  $Q = m(\Lambda_b^{*0}) - m(\Lambda_b^0) - 2m_\pi$

Reference	$M(\Lambda_b^0)$ , MeV/ $c^2$	$M(\Lambda_b^{*0}, \frac{1}{2}^-)$ , MeV/ $c^2$	$Q$ , MeV/ $c^2$	$M(\Lambda_b^{*0}, \frac{3}{2}^-)$ , MeV/ $c^2$	$Q$ , MeV/ $c^2$
Capstick	5585	5912	47	5920	55
Karliner	5619.7, CDF	$5929 \pm 2$	29	$5940 \pm 2$	40
Roberts	5612	5939	47	5941	49
Garcilazo	5625	5890	-15	5890	-15
Faustov	5622	5930	28	5947	45
Zhang	$5690 \pm 130$	$5850 \pm 150$	$-120 \pm 198$	$5900 \pm 160$	$-70 \pm 206$
A. Baccouche	5619.7, CDF	5920	20	5920	20

- Capstick: three quark relativized quark potential QCD model.
- Karliner: quark-potential model with the color hyperfine interaction.
- Roberts: non-relativistic quark model to the spectrum of baryons containing heavy quarks.
- Garcilazo: use a constituent quark model incorporating QCD, solving exactly the three-body problem.
- Faustov, Ebert: heavy  $Q$  and light- $qq$  using the relativistic quark model based on the quasipotential approach in QCD.
- Zhang: Nonperturbative formalism of QCD sum rules applied within HQET to calculate the mass spectra of the bottom baryon states.
- Aziza Baccouche: HQET at LO and NLO in the combined in the combined  $1/m_Q$ ,  $1/N_c$  expansions.

# Search of a Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Analysis Criteria (II)

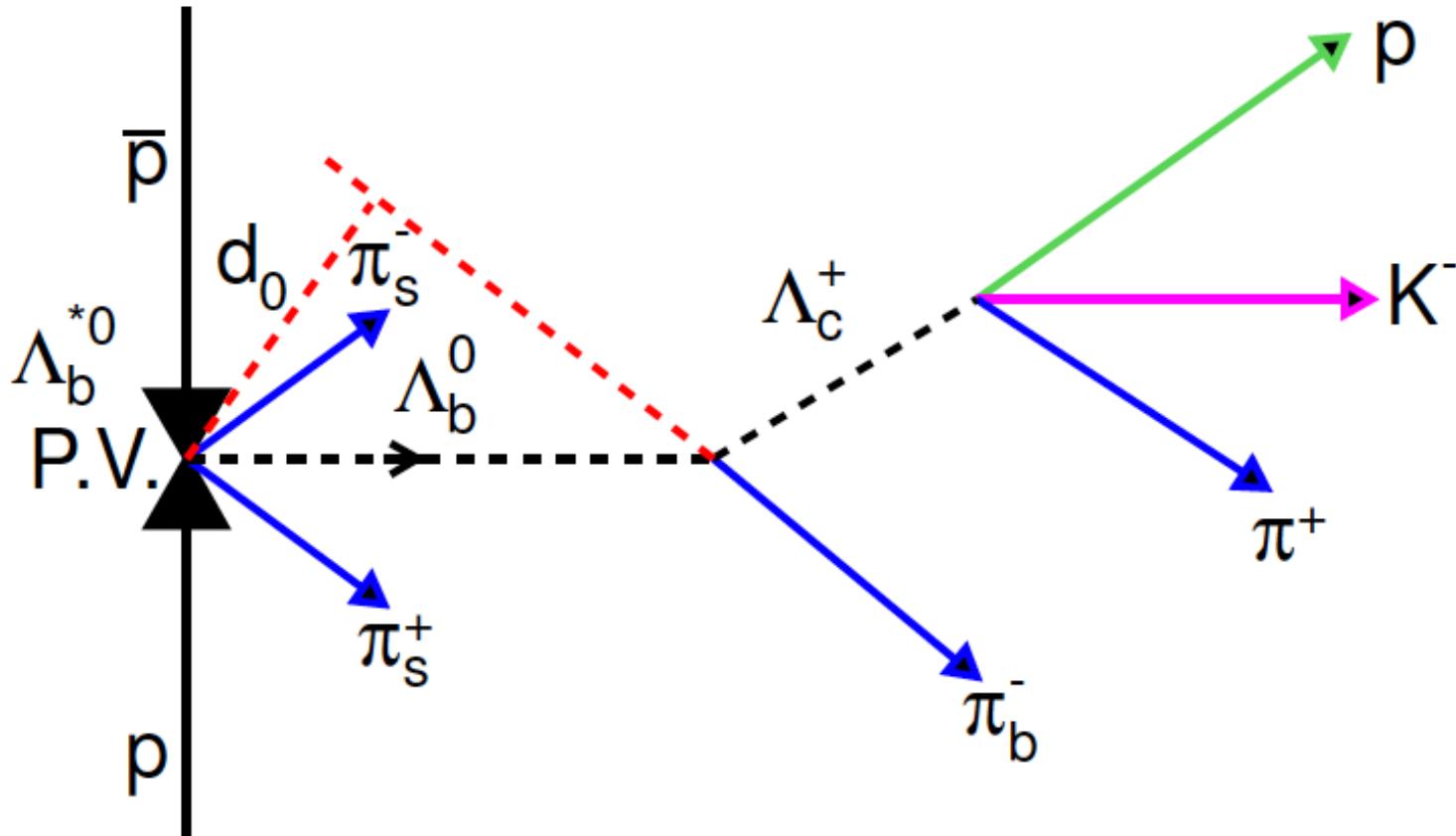
$$\begin{aligned}\Lambda_b^{*0} &\rightarrow \Lambda_b^0 \pi_s^- \pi_s^+ , \quad \Lambda_b^0 \rightarrow \Lambda_c^+ \pi_b^- , \\ \Lambda_c^+ &\rightarrow p K^- \pi^+\end{aligned}$$

## Soft pion $\pi_s^\pm$ tracks

- Hits *both in COT and Si- trackers, no tracks with Si only hits are allowed.*
- Tracks with a valid fit and proper error matrix.
- $p_T(\pi_s^\pm) > 200 \text{ MeV}/c$  to increase  $\Lambda_b^{*0}$  yield.
- fit  $\Lambda_b^0$ ,  $\pi_s^-$  and  $\pi_s^+$  to the common VX
- $p_T(\Lambda_b^{*0}) > 9.0 \text{ GeV}/c$  to keep soft pions within the kinematic acceptance.

# Trigger Sample Used for $\Lambda_b^*$ Search

## Two Displaced Track Trigger



# Search of a Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Significance

## Significance Estimate Based on Stat. Trials

- $\mathcal{H}_1$ : signal on top of the background.
- $\mathcal{H}_0$ : background.
- Generate  $\mathcal{H}_0$ , fit with  $\mathcal{H}_1$
- Use statistic,  $D = -2 \ln(\mathcal{L}_0/\mathcal{L}_1)$
- Search window:  
 $Q \in (6, 45) \text{ MeV}/c^2$
- $p = 2.3 \cdot 10^{-4}$  or  $3.5\sigma$

# Search of a Bottom Baryon Resonance $\Lambda_b^{*0}$ in CDF Data : Comparison with LHCb

## Comparison with Recent LHCb Results

- Result is consistent with the higher state  $\Lambda_b^{*0}(5920)$  found with  $\int \mathcal{L} dt = 1.0 \text{ fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$  (year 2011)
- LHCb reports also a state at  $\approx 5912 \text{ MeV}/c^2$  (same data)
- Assume
  - similar  $\sigma \cdot \mathcal{B}(\Lambda_b^{*0}(5912)) / \sigma \cdot \mathcal{B}(\Lambda_b^{*0}(5920))$
  - similar  $\epsilon(\Lambda_b^{*0}(5912)) / \epsilon(\Lambda_b^{*0}(5920))$ , actually  $\approx 1.0$ .
- Then the lack of a visible  $\Lambda_b^{*0}(5912)$  signal in the CDF II detector is statistically consistent within  $2\sigma$  with the  $\Lambda_b^{*0}(5912)$  reported by LHCb

# QCD Phenomenology of Heavy Quark Baryons : $\Sigma_b^{(*)}$ predictions (III)

## ⇒ Isospin Mass Splitting

Reference	$\Sigma_b^+ - \Sigma_b^-$ MeV/ $c^2$	$\Sigma_b^{*+} - \Sigma_b^{*-}$ MeV/ $c^2$
Chan	-6.12	-5.82
Lichtenberg	-7.1	-6.5
Capstick	-5.6	-5.4
Varga	-2.51	n/a

- mass splittings within the  $I = 1$  isospin triplets  $\Sigma_b^{(*)}$  arise due to a combination
  - the intrinsic light quark mass difference  $m(d) > m(u)$ .
  - electromagnetic interactions between quarks  $u$  and  $d$ .
- no previous experimental measurements

## ⇒ Natural Widths

Reference	$\Gamma(\Sigma_b, \frac{1}{2}^+)$ , MeV/ $c^2$	$\Gamma(\Sigma_b^*, \frac{3}{2}^+)$ , MeV/ $c^2$
Körner	~ 8	~ 15
Guo	(6.73... ...13.45)	(10.00... ...17.74)
Hwang, $\Sigma_b^{(*)+}$	4.35	8.50
Hwang, $\Sigma_b^{(*)-}$	5.77	10.44

- Only a few calculations (Korner:1994nh, Guo:2007qu, Hwang:2006df) of the  $\Sigma_b^{(*)}$  natural widths available:
  - $\Gamma(\Sigma_b, \frac{1}{2}^+) = 4.5...13.5 \text{ MeV}/c^2$
  - $\Gamma(\Sigma_b^*, \frac{3}{2}^+) = 8.5...18.0 \text{ MeV}/c^2$
  - no previous experimental measurements

# QCD Phenomenology of Heavy Quark Baryons : $\Sigma_b^{(*)}$ predictions (II)

Reference	$M(\Lambda_b^0),$ $\text{MeV}/c^2$	$M(\Sigma_b, \frac{1}{2}^+),$ $\text{MeV}/c^2$	$Q,$ $\text{MeV}/c^2$	$M(\Sigma_b^*, \frac{3}{2}^+),$ $\text{MeV}/c^2$	$Q^*,$ $\text{MeV}/c^2$
Capstick	5585	5795	70.4	5805	80.4
Albertus	$5643 \pm 20$	$5851 \pm 20$	$\sim 68.5$	$5882 \pm 20$	$\sim 99.5$
Jenkins	$5623.0 \pm 6.4$ , CDF I	$5824.2 \pm 9.0$	$\sim 61.6$	$5840.0 \pm 8.8$	$\sim 77.4$
Roncaglia	$5620 \pm 40$	$5820 \pm 40$	$\sim 60.4$	$5850 \pm 40$	$\sim 90.4$
Karliner	5619.7, CDF II	5814	$\sim 54.7$	5836	$\sim 76.7$
Narodetskii	5619.7, CDF II	5808, CDF II	$\sim 48.7$	5833	73.7
Garcilazo	5624	5789	24.4	5844	79.4
Faustov	5622	5805	43.4	5834	72.4
Zhang	$5690 \pm 130$	$5730 \pm 210$	$-100 \pm 247$	$5810 \pm 190$	$-20 \pm 230$
Liu	$5637_{-56}^{+68}$	$5809_{-76}^{+82}$	$\sim 32.4$	$5835_{-77}^{+82}$	$\sim 58.4$
Mathur	$5664_{-108}^{+103}$	—	$Q =$	—	$(\Sigma_b^* - \Sigma_b)$
$\beta = 2.1$			$1.4_{-33}^{+38}$	—	$22 \pm 12$
Mathur	$5672_{-110}^{+108}$	—	$53.4_{-36}^{+37}$	—	$(\Sigma_b^* - \Sigma_b)$
$\beta = 2.3$			—	—	$24_{-12}^{+13}$
Lewis	$5641_{-39}^{+26}$	$5795_{-30}^{+23}$	$\sim 14.4$	$5842_{-32}^{+33}$	$\sim 61.4$
$\beta = 1.9$					
$\Lambda_b^0$ , CDF II	$5619.7 \pm 1.2 \pm 1.2$	$Q$ -value definition:			
$\Lambda_b^0$ , LHCb	$5619.19 \pm 0.70 \pm 0.30$	$Q = M(\Sigma_b^{(*)}) - M(\Lambda_b^0) - m(\pi^\pm)_{\text{PDG}}$			
$\Lambda_b^0$ , ATLAS	$5619.7 \pm 0.7 \pm 1.1$				

# Measurement of Bottom Baryons $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ : Analysis Criteria (II)

$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi_s^\pm$  : Selection

Quantity	Requirement
soft track $\pi_s^\pm$	<b>basic COT and SVX II hit requirements,</b> <b>valid helix fit,</b> <b>valid err. matrix</b>
$p_T(\pi_s^\pm)$	$> 200$ MeV/c
$m(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi_b^-)$	$\in (5.561, 5.677) \text{ GeV}/c^2$ , i.e. $m_{\text{fitted}} \pm 3\sigma$
$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi_s^\pm$	<b>VX fit,</b> <b>no any constraint</b>
<b>VX fit ret. code</b>	= 0
$d_0(\pi_s^\pm)$	$< 0.1$ cm
$d_0(\pi_s^\pm)/\sigma_{d_0}$	$< 3.0$
$p_T(\pi_s^\pm)$	$< p_T(\pi_b^-)$
$p_T(\Sigma_b^{(*)\pm})$	$> 4.0$ GeV/c

## $\Sigma_b^{(*)\pm}$ Reconstruction

- Perform the analysis using  $Q$  value
  - $Q = m(\Lambda_b^0 \pi_s^\pm) - m(\Lambda_b^0) - m_\pi$  ,
- $m(\Lambda_b^0)$ , reconstructed  $m(\Lambda_c^+ \pi_b^-)$  mass.
- The mass resolution of the  $\Lambda_b^0$  signal and most of the systematic uncertainties cancel in the mass difference spectrum.

# QCD Phenomenology of Heavy Quark Baryons : $\Sigma_b^{(*)}$ predictions (I)

## ⇒ Mass Predictions

- Jenkins: HQET calculated in combined expansions in  $1/m_Q$ ,  $1/N_c$ .
- Gasiorowicz, Capstick, Rosner, Karliner: potential quark model, mass differences like  $\Sigma - \Lambda$ ,  $\Sigma^* - \Sigma$  are accounted largely by hyperfine splittings, hence the mass differences scale as  $1/m_Q$ .
- Narodetski: QCD string quark model.
- Roncaglia, Lichtenberg: Using regularities in the  $m$  and  $\Delta m$  of known hadrons apply semi-empirical mass formulas to predict the spectrum of heavy  $b$ -baryons.
- Shifman(+VZ), 1978; Ioffe, 1981: QCD Sum Rules; later by Liu, Zhang (2007-08).
- Mathur, Lewis: Lattice non-relativistic QCD (NRQCD).

- $m(\Sigma_b) - m(\Lambda_b^0) = 155...210 \text{ MeV}/c^2$
- $m(\Sigma_b^{(*)}) - m(\Lambda_b^0) = 200...240 \text{ MeV}/c^2$
- $m(\Sigma_b^{(*)}) - m(\Sigma_b) = \approx (10...20, 30...50) \text{ MeV}/c^2$

$\Sigma_b^{(*)\pm}$ 

# Measurement of Bottom Baryons $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ : Analysis Criteria (I)

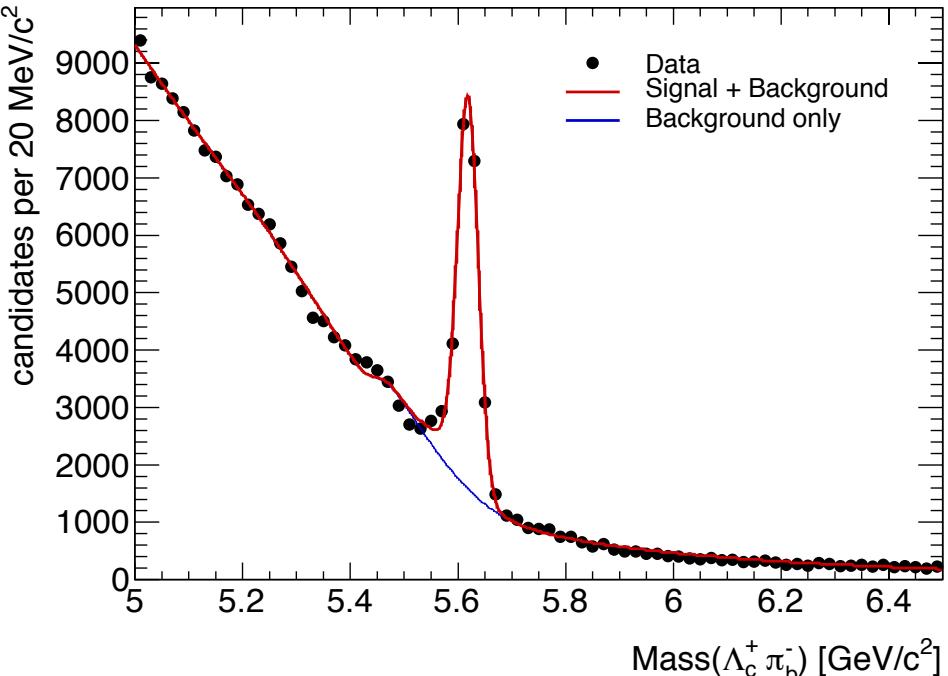
$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi_{soft}^\pm, \Lambda_b^0 \rightarrow \Lambda_c^+ \pi_b^-, \Lambda_c^+ \rightarrow p K^- \pi^+$$

Phys. Rev. D 85, 092011 (2012)  
[arXiv:1112.2808 [hep-ex]].

$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi_b^-$ : Reconstruction

Quantity	Requirement
$track(p, K^-, \pi^+, \pi_b^-)$	standard track quality criteria,
$p_T(\text{track})$	$> 400 \text{ MeV}/c$
$\Lambda_c^+ \rightarrow p K^- \pi^+$	<b>VX fit</b>
$m(\Lambda_c^+) \text{ cands.}$	$\in (m(\Lambda_c^+)_{\text{PDG}} \pm 18 \text{ MeV}/c^2)$
$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi_b^-$	<b>VX fit</b>
$m(\Lambda_c^+)$	$= m(\Lambda_c^+)_{\text{PDG}},$ <b>fit constraint</b>
$\text{Prob}(\chi^2_{3D})$	$> 0.01\%$
$ct(\Lambda_b^0)$	$> 200 \mu\text{m}$
$ct(\Lambda_b^0)/\sigma_{ct}$	$> 12.0$
$d_0(\Lambda_b^0)$	$< 80 \mu\text{m}$
$ct(\Lambda_c^+ \leftarrow \Lambda_b^0)$	$> -150 \mu\text{m}$
$ct(\Lambda_c^+ \leftarrow \Lambda_b^0)$	$< 250 \mu\text{m}$
$p_T(\pi_b^-)$	$> 1.5 \text{ GeV}/c$
$p_T(\Lambda_b^0)$	$> 4.0 \text{ GeV}/c$

Total CDF Luminosity of  $\int \mathcal{L} dt \approx 6 \text{ fb}^{-1}$   
collected by Two Displaced Track Trigger.



$N_{\Lambda_b^0} \approx 16\,300 \text{ cands.}$

# Measurement of Bottom Baryons $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ : Fit Model

## $\Sigma_b^{(*)\pm}$ Signal Model

- The signal is described by non-relativistic Breit-Wigner function
  - convoluted with a double Gaussian to model the detector resolution:  $\sigma_1$ ,  $\sigma_2$  and fraction  $f_1$  are fixed from MC.
  - the width of the Breit-Wigner is modified by P-wave factor: width is variable, specifically:

$$\Gamma(Q; Q_0, \Gamma_0) = \Gamma_0 \left( \frac{p_{\pi_s}^*}{p_{\pi_s}^{*0}} \right)^3,$$

$Q_0, \Gamma_0$  = mass, width at the pole (*i.e.* fit variables)

$p_{\pi_s}^*, p_{\pi_s}^{*0}$  = the momenta of the soft pion in the  $\Sigma_b^{(*)\pm}$  rest frame, off and on the resonance pole

## Backgr. Model and Complete Fitter

- Kinematically motivated background

$$\begin{aligned} \mathcal{BG}(Q; m_T, C, b_1, b_2) &= \sqrt{(Q + m_\pi)^2 - m_T^2} \\ &\times \mathcal{P}^2(Q; C, b_1, b_2), \\ m_T &= 0.140 \text{ GeV}/c \end{aligned}$$

- $Q$ -value spectra for  $\Sigma_b^{(*)+}$  and  $\Sigma_b^{*-}$ :** two narrow structures on top of a smooth background with a threshold.
- Independent LH for  $\Sigma_b^{(*)+}$  and  $\Sigma_b^{*-}$  candidates.** Every  $Q$ -value unbinned spectrum is fit over the range 0.003–0.210  $\text{GeV}/c^2$
- unbinned fitter,  $2 \times 3 + 3$  pars.**

# Measurement of Bottom Baryons $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ : Signals' Significance (II)

Statistical significances of the observed signals against various null hypotheses.  $N_\sigma$  is the calculated number of Gaussian standard deviations based on  $\text{Prob}(\chi^2)$ .

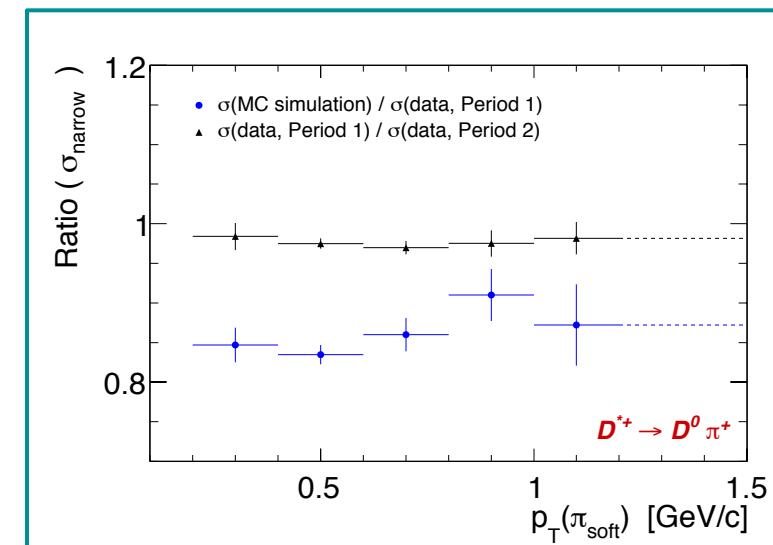
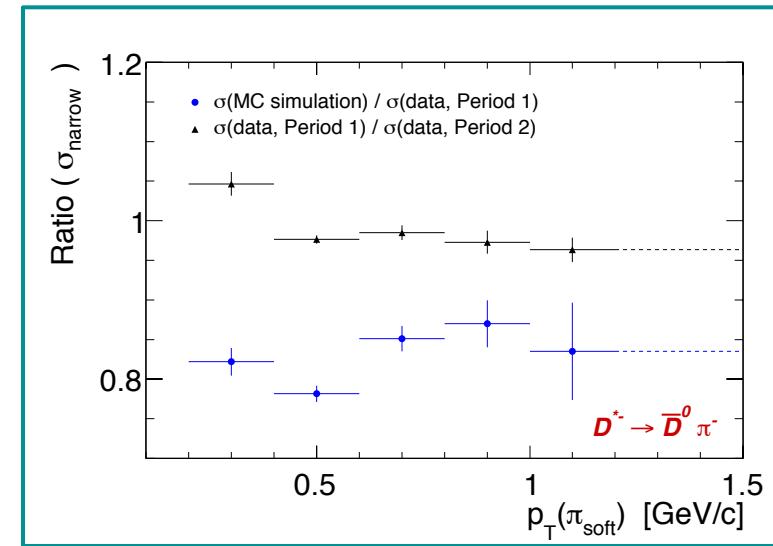
$\mathcal{H}_0$	States	$N_\sigma$	$\mathcal{H}_1$
<b>Any single wide enhancement</b>	$\Sigma_b^{(*)-}$	6.7	<b>Two narrow structures</b>
	$\Sigma_b^{(*)+}$	6.1	
<b>No structures</b>	$\Sigma_b^{(*)-}$	10.7	<b>Any single wide enhancement</b>
	$\Sigma_b^{(*)+}$	13.2	
<b>No <math>\Sigma_b</math>, with <math>\Sigma_b^*</math>, <math>\Gamma_{02} = 12 \text{ MeV}/c^2</math></b>	$\Sigma_b^{(*)-}$	7.6	<b>Two narrow structures</b>
	$\Sigma_b^{(*)+}$	7.9	
<b>No <math>\Sigma_b^*</math>, with <math>\Sigma_b</math>, <math>\Gamma_{01} = 7 \text{ MeV}/c^2</math></b>	$\Sigma_b^{(*)-}$	10.0	<b>Two narrow structures</b>
	$\Sigma_b^{(*)+}$	12.5	
<b>No structures</b>	$\Sigma_b^{(*)-}$	12.4	<b>Two narrow structures</b>
	$\Sigma_b^{(*)+}$	14.3	

The results of this study establish conclusively the  $\Sigma_b^{(*)-}$  and  $\Sigma_b^{(*)+}$  signals with significance of  $6\sigma$  or higher.

# Measurement of Bottom Baryons $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ : Systematic Uncertainties

## Systematic Uncertainties

- The uncertainty due to the CDF tracker momentum scale.
  - knowledge of the magnet field
  - energy loss in the tracker's material
  - specific to soft pion tracks  $\pi_s^\pm$ , data driven:
    - use reference modes reconstructed with the same data sample:  $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi_s^+$ ,  $\Sigma_c^0 \rightarrow \Lambda_c^+ \pi_s^-$ ,  $\Lambda_c^{*+} \rightarrow \Lambda_c^+ \pi_s^+ \pi_s^-$ , and  $D^{*+} \rightarrow D^0 \pi_s^+$ .
- The uncertainty due to the resolution model described by the sum of two Gaussians, dominating width measurements:
  - referenced mode:  $D^{*\pm}$  reconstructed down to  $p_T(\pi_s^\pm) = 200 \text{ MeV}/c$  in data and in MC.
  - compare the mass resolution found in data and MC
- The choice of background model.
- An uncertainty due to the choice of  $Q$ -value fit range.
- Uncertainty in the absolute mass quote: from the external source, CDF published:  
 $M(\Lambda_b^0) = 5619.7 \pm 1.2(\text{stat}) \pm 1.2(\text{syst}), \text{ MeV}/c^2$
- propagate using a large number of generated and fitted statistical trials.



# Measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ : Systematic Uncertainties Summary

Summary of the systematic uncertainties listed in the following order:  
 mass scale, resolution, choice of background model, and fit range. The  
 total systematic uncertainty is obtained by adding all the associated  
 uncertainties in quadrature. The last column shows the percentage of  
 the total systematic uncertainty relative to its central value.

Measurable quantity	Scale	Resolution	Background	Fit range	Total	Percentage
$Q(\Sigma_b^-)$ [MeV/ $c^2$ ]		+0.06	+0.04	+0.02	+0.07	+0.1
	-0.38	-0.07	-0.04	-0.03	-0.39	-0.7
$\Gamma(\Sigma_b^-)$ [MeV/ $c^2$ ]	+0.20	+0.85	+0.50	+0.50	+1.13	+23
	-0.20	-0.87	-0.50	-0.51	-1.14	-23
$Q(\Sigma_b^{*-})$ [MeV/ $c^2$ ]		+0.06	+0.06	+0.02	+0.09	+0.1
	-0.56	-0.08	-0.06	-0.09	-0.58	-0.8
$\Gamma(\Sigma_b^{*-})$ [MeV/ $c^2$ ]	+0.20	+0.65	+0.30	+0.50	+0.89	+12
	-0.20	-0.96	-0.30	-0.90	-1.36	-18
$Q(\Sigma_b^+)$ [MeV/ $c^2$ ]		+0.07	+0.05	+0.02	+0.09	+0.2
	-0.35	-0.12	-0.05	-0.03	-0.38	-0.7
$\Gamma(\Sigma_b^+)$ [MeV/ $c^2$ ]	+0.20	+0.94	+0.40	+0.50	+1.16	+12
	-0.20	-0.90	-0.40	-0.51	-1.12	-12
$Q(\Sigma_b^{*+})$ [MeV/ $c^2$ ]		+0.06	+0.10	+0.02	+0.12	+0.2
	-0.52	-0.13	-0.10	-0.09	-0.55	-0.8
$\Gamma(\Sigma_b^{*+})$ [MeV/ $c^2$ ]	+0.20	+0.64	+0.50	+0.50	+0.97	+8.5
	-0.20	-1.01	-0.50	-0.90	-1.46	-13

# Measurement of Bottom Baryons $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ : Conclusions

Conclusions: Phys. Rev. D 85, 092011 (2012)

[arXiv:1112.2808 [hep-ex]]

- The masses and widths of the  $\Sigma_b^{(*)\pm}$  baryons have been measured using a sample of  $N(\Lambda_b^0) \approx 16\ 300$ , with  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  mode. The luminosity  $\int \mathcal{L} dt \approx 6 \text{ fb}^{-1}$
- The first observation (CDF) of the  $\Sigma_b^{(*)\pm}$  bottom baryons has been confirmed with every individual signal reconstructed with a significance well in excess of  $6\sigma$ .
- The isospin mass splittings within the  $I = 1$  triplets of the  $\Sigma_b$  and  $\Sigma_b^*$  states have been extracted for the first time.
  - $m(\Sigma_b^{*-}) > m(\Sigma_b^{*+})$  following a pattern common to most of the known isospin multiplets.
    - ◊ due to  $m(d) > m(u)$
    - ◊ the larger electromagnetic contribution due to electrostatic Coulomb forces between quarks in  $\Sigma_b^{*-}$  states than in  $\Sigma_b^{*+}$  ones.
- The natural widths of the  $\Sigma_b^\pm$  and  $\Sigma_b^{*\pm}$  states have been measured for the first time. The measurements are in agreement with theoretical expectations.